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An Evaluation Of Spatial Variability Of Water Stress Index Across The United States: Implications Of Supply And Demand In The East Vs The West

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AN EVALUATION OF SPATIAL VARIABILITY OF WATER STRESS INDEX ACROSS THE UNITED STATES: IMPLICATIONS OF SUPPLY AND DEMAND IN THE EAST VS THE WEST

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ABSTRACT

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In order to support both human and environmental needs, high quality fresh water must be available when and where it is required. As a metric for indicating unsustainable water usage, WSI is only useful when the values reflect accurate interactions between supply and demand; however, the complexity of temporal and spatial variability of available fresh water complicates the analysis of water stress.

The overall goal of this project was to investigate the spatial variability of water stress across the United States and the appropriate spatial scale for management decisions. To accomplish this, a national dataset describing spatial distribution and breakdown of water supply and demand, land use characteristics, and population demographics was compiled at the watershed scale. Water stress index was calculated for each 10 digit hydrologic unit code in the US by developing a surface water routing program to calculate water stress and discharge. The right to withdrawal freshwater is closely regulated by government entities that need accurate information regarding unsustainable practices. In the national scale analysis, patterns of population and public

supply induced water stress appeared when calculations were performed on a higher resolution in the East; while large scale water stress in the West remained similar to lower resolution maps. Due to spatial variability, calculations should be performed at the highest practical resolution to preserve effects of population centers.

CHAPTER 1. INTRODUCTION

1.1 Background

In order to support both human and environmental needs, high quality fresh water must be available when and where it is required in order to support sustained agricultural, industrial and municipal growth (Shiklomanov, 2000). As a vital natural resource with competing consumers, the right to withdrawal freshwater is closely regulated by government entities who need accurate information regarding unsustainable practices.

1.1.1 Water Stress

Water stress is the term most commonly used to express the inability to meet human demand given available supply; however, the complexity of temporal and spatial variability of available fresh water complicates the analysis of water stress (Oki et. al., 2001; Sabo et al., 2010). In order to strengthen accuracy, water stress studies should include human impacts to hydrological processes due to the wide-scale manipulation of runoff, extraction of groundwater reserves, and introduction of contaminants into freshwater sources (Fallenmark, 1997; Oki and Kanae, 2006; Alcamo et al., 2003; Vorosmarty et al., 2010).

The water stress index (WSI) is a metric derived in order to express water stress using the relationship between water supply and demand on a numerical scale that can be easily compared across regions (Oki et al., 2001). Defined as the ratio of water demand to water supply, WSI combines a water balance of the hydrologic cycle with human consumption of freshwater sources. The demand to supply concept has been applied by researchers on regional, country, and global scales to investigate the state of global water stress.

In addition to the widespread use of WSI, several studies have taken different approaches to estimating water stress. Oki and Kanae's (2006) study on global hydrological cycles shows the importance of including human impacts on freshwater resources, specifically the need to look at both water availability and water withdrawals in analysis of water stress. The metric, in this case water scarcity index, is the ratio of reported annual water withdrawals less desalinized water supply to annual renewable freshwater resources from model estimates of river discharge. Based on this assessment, approximately 2.4 billion people are currently living in highly water-stressed areas. Alcamo et al. (2003) used the criticality ratio, water need over available water resources, to evaluate pressure on aquatic systems and estimate that 24% of global rivers are severely stressed. Oftentimes, downstream areas show greater water stress and biodiversity threat than upstream areas due to accumulation of contaminants, less water availability, and upstream infrastructure (Vorosmarty et al., 2006).

The WSI can vary continuously from zero to values much greater than 1, so it is useful to set stress threshold at a level appropriate to meet both ecosystem and human needs. Since local biota also require freshwater for survival, not all of the surface water supply can be allocated for human use; therefore, WSI greater than 0.4 is considered stressed, and WSI greater than 0.6 is considered severely stressed (Oki et al., 2001; Alcamo et al., 2003; Sabo et al., 2010). Vorosmarty et al. (2010) used a slightly different threshold to predict human water scarcity threats and consider values greater than 0.5 to indicate moderate threat, and values greater than 0.75 to indicate severe threat.

Another metric, the human water scarcity threat takes the ratio a step further including the technological benefits of water resource improvements when approximating stress. Even with the additional benefit of infrastructure investment, Vorosmarty et al. (2010) estimate a moderate to severe human water scarcity threat for 30 of the 47 largest rivers in the world. Whether positive or negative, contemporary researchers agree that human impacts on hydrological systems are a vital component when investigating water stress.

1.1.2 Spatial Scale

Negative and even positive, human impacts to river systems can accrue downstream due to spatial legacy. Downstream freshwater sources often have degraded quality and quantity when compared to their upstream counterparts; therefore, water stress is dependent on the relative position in the watershed (Vorosmarty et al., 2010).

Vorosmarty et al. (2010) further show that the significance of upstream water technology on downstream systems plays a major factor in determining global water sustainability. Alcamo et al. (2003) analyzed how water withdrawals from different users such as municipal, industrial and agriculture affects water stress spatially. Because downstream users are impacted by upstream users, the quality and the quantity of freshwater resources needs to be analyzed on regional scales in order to decipher freshwater sustainability.

Excessive use by upstream users may be masked by abundant downstream supply if the spatial scale of analysis of water stress is too coarse. Conversely, headwaters tend to have a higher average runoff depth than larger watersheds, so the spatial variability of supply is not well-captured at low resolution (Sabo et al., 2010). In order to present an accurate representation of water stress, calculations should be performed at a resolution that reflects the spatial variation of demand and supply, and at the scale of interest for management and policy decisions (Seyfried and Wilcox 1995).

Oki et al. (2001) used the concept of water scarcity to determine the global distribution of water stress on a 0.5 x 0.5 grid, rather than by country. As one of the first studies to look more closely at how spatial scale effects water stress calculations, they were able to highlight specific regions with severe water stress such as the Yellow River, Indus, Ganges, and Amu-Darya basins and the Midwest United States. Additionally, they showed that the dense population distribution in China impacted water demand generating water stress; a concept this paper further explores within the United States.

1.1.3 Water Policy

Since human impacts on freshwater sustainability are critical when investigating global water stress, the societal constraints on water use might have an impact on water stress values. The evolution of water policy across the United States highlights the difference between east and west water supply. Abundant water supply in the East did not require strict allocation rules; therefore, policy remained similar to European, riparian laws which gave rights to all property owners who had access (Apple, 2001). Conversely, as the West developed, limited water supply necessitated new doctrine for allocation. The emergence of prior appropriation separated the property rights from water rights, creating a new value associated with water (Apple, 2001). Despite the differences in water law, both schools of thought agree that an individual does not own the actual water, rather the right to access it for beneficial use. The drastic difference in water supply across the United States has promoted varying approaches to water policy; conversely this project explores the many factors, including water policy itself, that could also be influencing water stress.

1.2 Project Summary

The application of various water management policies, large scale water infrastructure projects, and changing national demographics has affected water stress over the last century in the United States (Sabo et al. 2010). The change in national demographics leading to increases in urban populations has led to increasing water stress in highly populated counties at a faster rate than less populated areas. In the eastern US, water policy such as large multi-state agreements have a greater potential to redistribute water stress. While in the western US, supply is limited so that large infrastructure projects have less potential to eliminate water stress through redistribution.

The overall goal of this project is to investigate the spatial variability of water stress across the United States and the appropriate spatial scale for management decisions. In particular, it will address the following underlying science questions:

1. How does the water stress index vary spatially in relation to supply and demand factors, including ecoregion, political accounting units, population, price, and irrigation needs.
2. Is the dominant control on the spatial variability of water stress index different in the eastern versus the western United States?

These questions will be addressed through the following specific objectives:

- Compile a national dataset at the watershed scale describing the spatial distribution and breakdown of water supply and demand, land use characteristics, and population demographics.
- Evaluate how water stress changes spatially by developing a surface water routing program to calculate water stress.
- Synthesize the factors influencing water stress at a regional scale, including supply and demand characteristics, spatial distribution of population and land use, and historical water policy institutions.

From studying current literature on water stress (e.g., Sabo, et al. 2010), it is hypothesized that the spatial variability of water stress in the western US is lower and is most effected by limited supply. Furthermore, it is hypothesized that water stress in the eastern US is dependent on the location of population centers within large watershed systems and spatial variability is controlled by locations of high demand.

1.3 Thesis Format

This thesis is composed of six chapters, including: context, methods, water stress analysis, regional case study, and conclusions. Chapter 2 discusses the historical and ecological context of water stress in two hydrologic regions: the South Atlantic Gulf and the Colorado River Basin. Chapter 3, the methods section, discusses the process for calculating water stress index, how the datasets were converted into a useable format, and the unique routing process for streamflow. Chapter 4 discusses the results of the national analysis of water stress including a breakdown of the effect various supply and demand sectors have on water stress. Chapter 5 revisits the case study regions to investigate the factors influencing water stress. Lastly, Chapter 6 discusses the overall spatial variability of water stress, makes recommendations for scale, as well as future work based on these results.

CHAPTER 2. CONTEXT OF WATER STRESS IN THE EAST VS WEST

2.1 Hydrologic Study Regions

In order to investigate differences between water stress in the East versus the West, the national analysis was viewed in context of two hydrologic regions in the United States. The ecology and historical water conflicts of the regions will be reviewed before moving ahead to the water stress analysis methods and results. Figure 2-1 shows the location of the two regions: the South Atlantic Gulf and the Colorado River Basin.

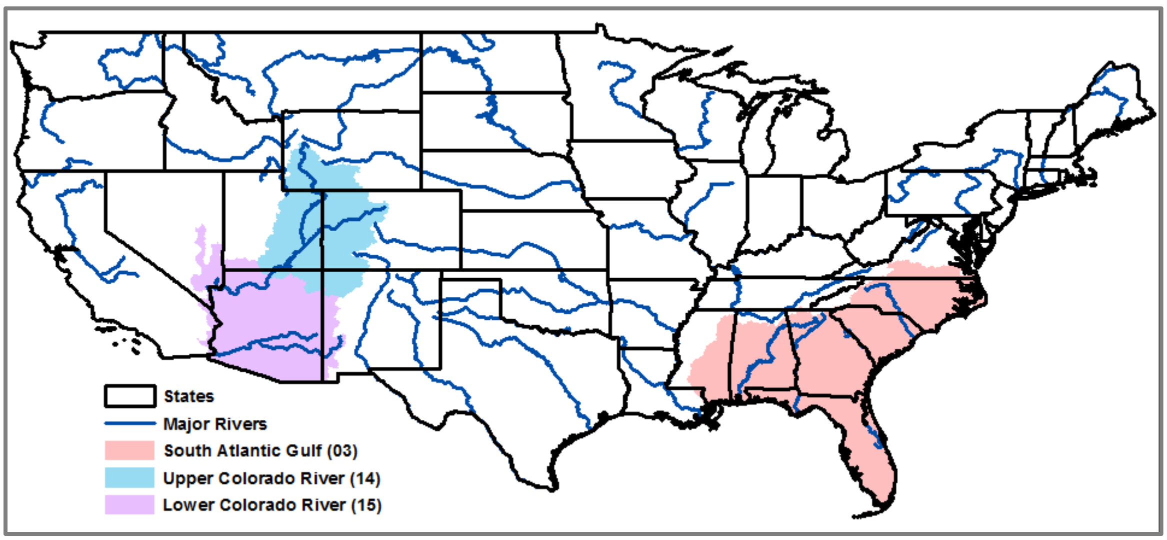

Figure 2-1 Location of study regions

2.2 Eastern vs Western Ecological Boundaries

2.2.1 South Atlantic Gulf Eco-Regions

The South Atlantic Gulf region, shown in Figure 2-2, encompasses Virginia, North Carolina, South Carolina, Georgia, Florida, Alabama and Mississippi. A small portion of the region is in Tennessee and Louisiana, but these states were not included in state wide analysis discussed in Chapter 5. Within the South Atlantic Gulf, there are 1,584 watersheds, and five major rivers: the Alabama, Chattahoochee, Pee Dee, Savannah and St. Johns Rivers. Additionally, there are 1,073 counties. The three most populated cities in the region include Charlotte, NC, Atlanta, GA, and Jacksonville, FL (US Census 2010). According to the 2007 Agricultural Census, the South Atlantic Gulf has the 4th highest number of farms in the US, 4-6% of them are irrigated (NASS 2007).

The ecological provinces that make up the South Atlantic Gulf region include: Atlantic Coastal Flatlands, Coastal Plains and Flatwoods, Everglades, Mixed Forest and the Southern Appalachian Piedmont (McNab et al., 2005). The northeastern portion is mountainous with plentiful, evenly distributed annual precipitation, which can include high intensity storms due to hurricanes. Moving south, the mountains start to transition into valleys with maritime climate conditions, where hot, humid summers are most often accompanied with brief droughts. The outer coastal plains are fragmented with well drained alluvial plains and poorly drained soils over shallow water tables; additionally, the plains receive abundant precipitation. Finally, the southern tip of the

Everglades has a subtropical maritime climate with very rainy summers and dry winters (McNab et al., 2005). Figure 2-2 shows the ecological features of the South Atlantic Gulf.

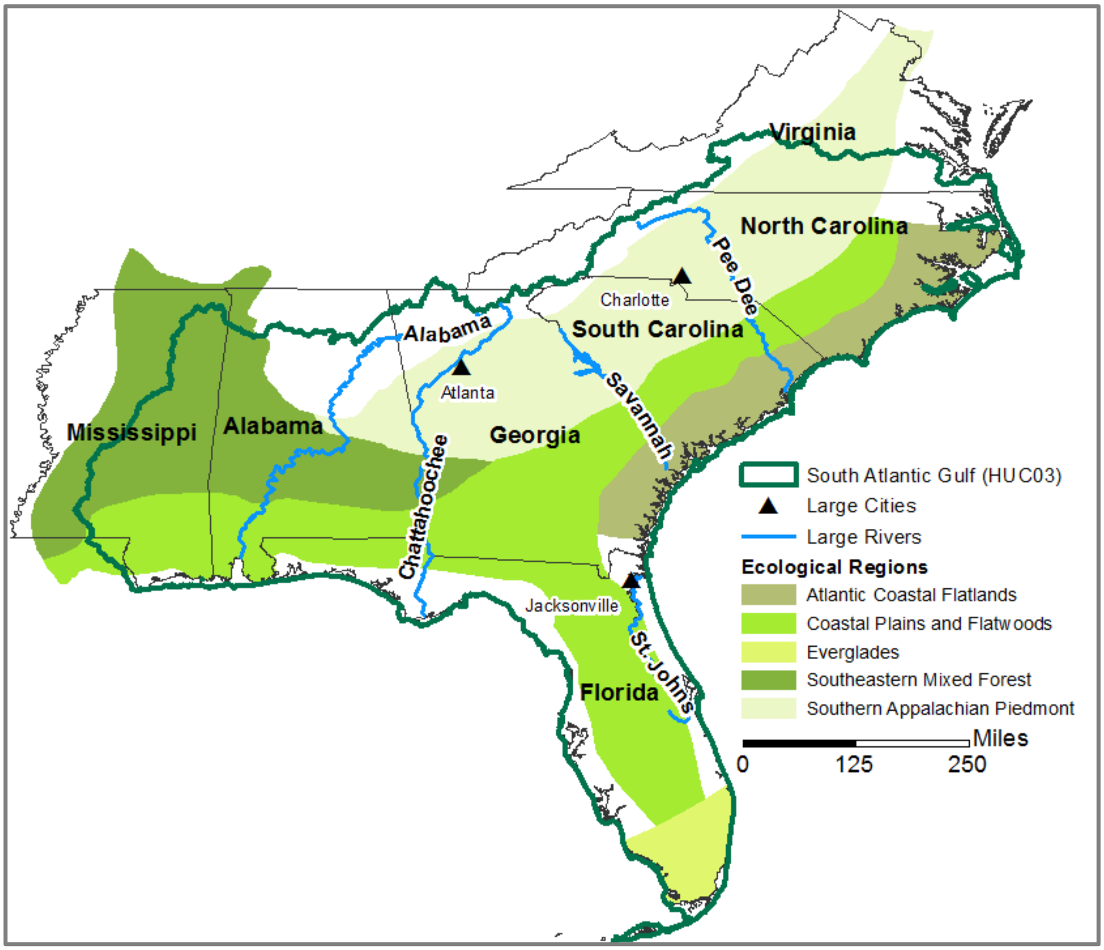

Figure 2-2 Map of the South Atlantic Gulf region

2.2.2 Colorado River Basin Eco-Regions

The Upper and Lower Colorado River regions, shown in Figure 2-3, include all of Arizona and portions of Wyoming, Nevada, Utah, Colorado, New Mexico, and a small portion of California. California was left out of statewide analysis because only a small portion of the state is physically within the Lower Colorado Basin. Although large scale water transfers from the Colorado River system to California (as well as Nevada and Arizona) impact the Colorado (Sabo et al. 2010), this connection is reflected in the increased water stress at the point of water withdrawal within the Colorado basin. The Upper Region has 530 watersheds and the Lower Region has 1081, totaling 1611 watersheds in the area of interest. Major rivers in the Colorado River Basins include: the Green, Gila, Salt, and Colorado Rivers. Within the combined Colorado River Basins there are 88 counties. The three regional cities with the highest population include: Las Vegas, NV, Tucson, AZ, and Phoenix, AZ (US Census 2010). The Upper Region has between 10-24 million acres of farmland, 4-6% of which is irrigated. Conversely the Lower Region has 25-49 million acres of farmland with less than 4% of that being irrigated (NASS 2007).

Together, the Colorado River Basin contains 7 different ecological provinces: American Semi-desert, Arizona-New Mexico Mountain Semi-Desert, Colorado Plateau, Intermountain Semi-Desert and Desert, Nevada-Utah Semi-Desert, Rocky Mountain Steppe (McNab et al. 2005). The semi-desert and desert regions have similar climates with overall low annual precipitation, mostly occurring in the winter as snowfall with occasional thunderstorms in the late summer months. Temperatures vary strongly based on elevation: higher altitudes are colder than lower altitudes. These semi-deserts and deserts are fragmented with canyons, plateaus, plains, and low mountains. Most notable geographic areas are the Grand Canyon and the Mojave Desert. The Rocky Mountain Steppe has long, cold winters with heavy snowfall which melts in the summer to generate the river discharge. This area is mainly mountains dissected by narrow river valleys (McNab et al. 2005). Figure 2-3 shows the ecological regions of the Upper and Lower Colorado River Basins.

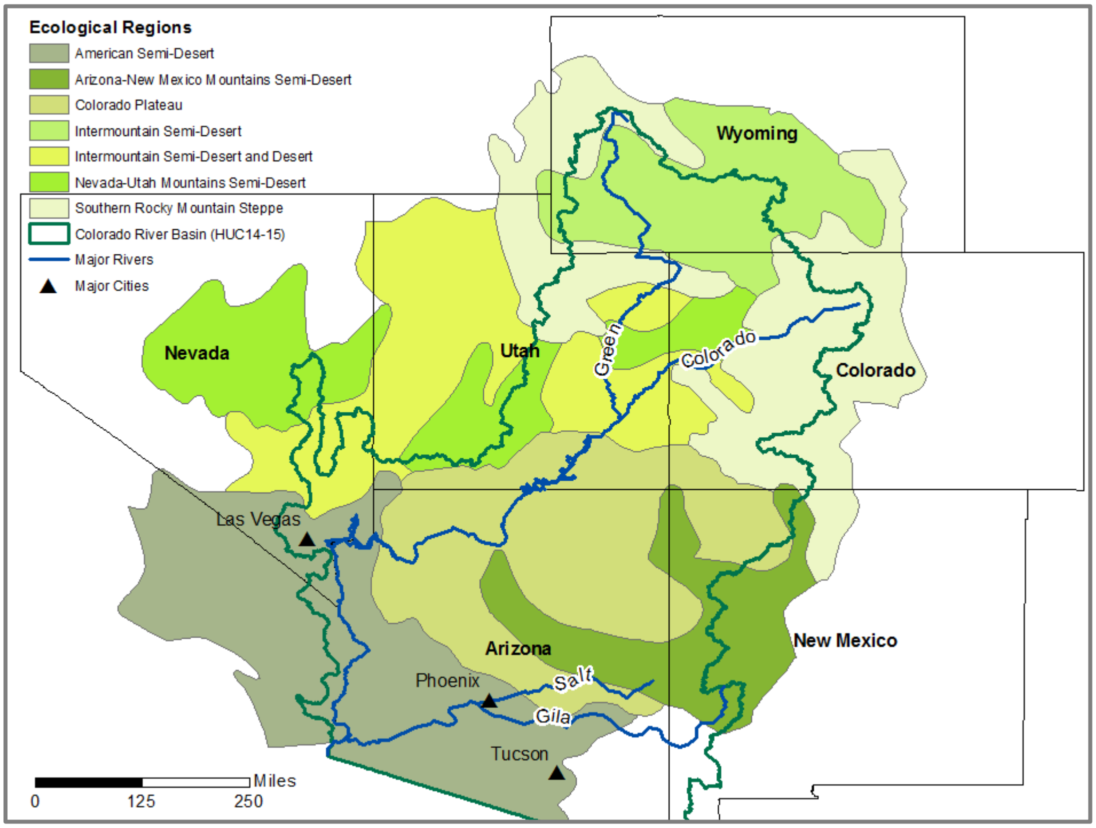

Figure 2-3 Map of the Upper and Lower Colorado River Basins

2.3 Eastern vs Western Water Policy

The two regions follow different doctrine when it comes to water rights. The eastern United States has adopted riparian water rights, or reasonable and beneficial use doctrine. Because each state has equal claim to surface water, disputes over interstate rivers and reservoirs require negotiations among the states, often involving litigation or Congressional approval (Sherk, 1994). A strong difference in the western US is that water ownership is disconnected from land ownership because the West follows prior appropriation doctrine, otherwise known as first in time, first in right. Due to the limited total supply and sparse surface water supply in the Southwest, water rights regularly cause conflicts both across state boundaries and even country boundaries.

2.3.1 South Atlantic Gulf Water Conflicts

In the last few decades, litigations over water use have greatly increased in the South Atlantic Gulf region (Sherk, 1994). With population centers rapidly expanding and climate change altering precipitation events, eastern states are apprehensive of proposed water projects by neighboring states. Because the East follows riparian or reasonable use doctrine, any state benefiting from the water source has equal claim to its use. These conflicts can last decades, are often argued in court, and sometimes remain unresolved.

2.3.1.1 The Apalachicola-Chattahoochee-Flint River System and the Alabama-Coosa-Tallapoosa River System

The city of Atlanta, Georgia withdraws water from the Lake Lanier reservoir, the head waters for the Apalachicola-Chattahoochee-Flint (ACF) river system (Couch et al., 1996). Downstream of the ACF system are Alabama and Florida. In order to keep up with the demands of a rapidly growing metropolis, Georgia and the Army Corp of Engineers drafted a plan to release more water from the Buford Dam which regulates the level in Lake Lanier. Alabama, greatly concerned about downstream water quality, challenged the plan in 1990 arguing the Environmental Impact Statement (EIS) did not adequately investigate environmental quality. Joining the litigation, Florida intervened to negate environmental impacts on the Apalachicola Bay where a thriving shrimping economy supports the panhandle region (Water Policy Institute, 2009). In 1993 a proposal for large water transfer from Lake Allatoona in the Alabama-Coosa-Tallapoosa (ACT) river system to supply water to Atlanta further heated the Tri-State Water Dispute.

Getting nowhere, the ACF Compact and the ACT Compact were formed in 1997 to try and negotiate water allocation among the three states outside of the court system; unfortunately, attempted mediation spanned 10 years ending in more litigation. In 2009, the US Supreme Court denied an appeal by Georgia to overturn a previous invalidation of a water sharing agreement. Relocating water from Lake Lanier for consumptive use is considered a major operational change and requires Congressional approval (Water Policy Institute, 2009). The Tri-State Water Dispute is a perfect example of how the competing demand for water from public supply, industry, and ecosystem services creates conflicts between the users. Despite the abundant supply of water in the East, increased demand has caused local water stress.

2.3.1.2 Other Disputes

The Savannah River separates South Carolina and Georgia, and since both states have equal claim over the water supply, it has been an ongoing source of conflict. Unlike the

ACT and ACF compacts, the conflict surrounds water quality issues due to the Savannah River Plant Nuclear Facility. Increasing contamination is limiting the supply of usable water, but the states are still tied up in court cases and mediation attempts involving the Department of Energy and the South Carolina Department of Health and Environmental Control (Sherk, 1994).

Virginia and North Carolina were also involved in a lengthy battle over the Roanoke River starting in 1987 (Sherk, 1994). Along with the Army Corp of Engineers, Virginia proposed to divert water to Lake Gaston from the Roanoke River. After nearly a decade of court battles and appeals, the proposed diversion was approved in 1991.

2.3.2 Colorado River Basin Water Conflicts

The American West has an arid climate and expansive agricultural areas contributing to a colorful history of water disputes concerning the allocation of water rights (Apple 2001). Due to the constraints of physically available supply, water stress in many parts of the West can be considered supply-limited rather than demand driven. A strong difference relative to the South Atlantic Region is that water ownership is disconnected from land ownership because the West follows prior appropriation doctrine, otherwise known as first in time, first in right. Due to the limited quantity and sparse locations of surface water supply in the Southwest, water rights regularly cause conflicts both across state and country boundaries.

2.3.2.1 Colorado River Compact

Nearly a century ago, the seven states withdrawing water from the Colorado River ratified a compact clearly defining water allocation to each state. The Upper Colorado Basin states: Colorado, Utah, Wyoming, and New Mexico, split 7.5 million acre-ft/year, while the Lower Colorado Basin states: California, Arizona and Nevada, share 8.5 million acre-ft/year (Meyers, 1966). At the time, negotiations were difficult because the states refused to agree on a uniform metric by which to calculate each state's percentage of the supply. Engineers performed a water mass balance across all seven states taking into account irrigated acres, diversions, consumption, evaporation, and virgin flow. This report even led the commissioners to base their decision on net depletion, which included evapotranspiration throughout the river system, rather than the prior standard consumptive use, which only considered withdrawal (Meyers, 1966). The expansive dispute among the seven states was almost entirely based on supply, such that changing proportions of demand in the states is not a sufficient argument to renegotiate the terms of the Colorado River Compact (Meyers, 1966).

CHAPTER 3. METHODS

3.1 Introduction

In order to determine the water stress index for every watershed in the contiguous United States (US), national scale datasets depicting water use and water availability were needed in consistent formats and scales. The USGS identifies national hydrologic regions using a nested series of Hydrologic Unit Codes (HUC). At the coarsest resolution, the US is composed of 21 major hydrologic regions represented by a 2-digit number. These regions are further broken down into sub-regions, which are further divided up through 6 levels of classification based on watershed drainage areas (Seaber et al., 1987). The 5th level, or 10-digit HUC, was chosen as the map boundaries for this analysis. Additionally, due to lack of available information, a unique process was created to determine the order of watersheds in a stream network. This chapter will explain the water stress index equation, describe the datasets and conversion processes, and the approach for watershed routing.

3.2 Water Stress Index Calculation

Water stress index (WSI), also known as water scarcity index, is a metric to denote areas of concern for freshwater sustainability calculated as the ratio of demand over supply

(Oki and Kanae, 2006). WSI values for each individual 10-digit HUC were calculated as follows:

$$WSI_i = \frac{W_i}{R_i + \sum Q_{i-1}} \qquad \text{Equation 3-1}$$

where $\sum Q_{i-1}$ is the upstream flow entering the HUC boundary, R_i is the locally generated runoff within the boundary, and W_i is the total water withdrawal within the boundary. The volume of water discharged from each 10-digit HUC boundary is the total local runoff plus the upstream flow minus the surface water withdrawals, calculated as follows:

$$Q_i = R_i + (\sum Q_{i-1}) - S_i \qquad \text{Equation 3-2}$$

where S_i is the surface water withdrawal within the boundary.

An iterative program was written to calculate upstream flow, $\sum Q_{i-1}$, as discharge, Q_i, from all upstream HUCs, in the same step as WSI. Using a system of ranking based on routing information, the 10-digit HUCs were ordered so that all upstream discharge calculations were performed prior to downstream calculations; therefore, the value $\sum Q_{i-1}$ was already known. If the discharge is negative, such as the case when groundwater constitutes a majority of the supply, the Q_i value is reset to zero.

3.3 Datasets

In order to calculate WSI, values for total runoff, total water withdrawals, and surface water withdrawals are needed for each individual 10-digit HUC. A combination of recorded data and simulated data was used.

3.3.1 Downloaded Nationally Recorded Datasets

The United States Geological Survey (USGS) provides several national datasets. State, local and tribal governments report water withdrawal data to the USGS and the average daily withdrawals over the period from 2001 to 2005 are compiled by county for each category and available as an Excel workbook (Kenny et al., 2009). The 2005 Water Use Table reports average daily withdrawals by county broken down by type of water supply and by type of water user. The values for total average daily freshwater withdrawals (both surface and groundwater) constituted the demand value in the WSI calculation, W_i.

The tabulated data was converted to a spatial dataset using the Federal Information Processing Standard (FIPS) values for each county. Since FIPS values are also used in the national atlas county map, the water withdrawal by county data was joined to the county level shapefile within ArcGIS, a program for mapping and spatial analysis. Figure 3-1 shows the total water withdrawal information by county.

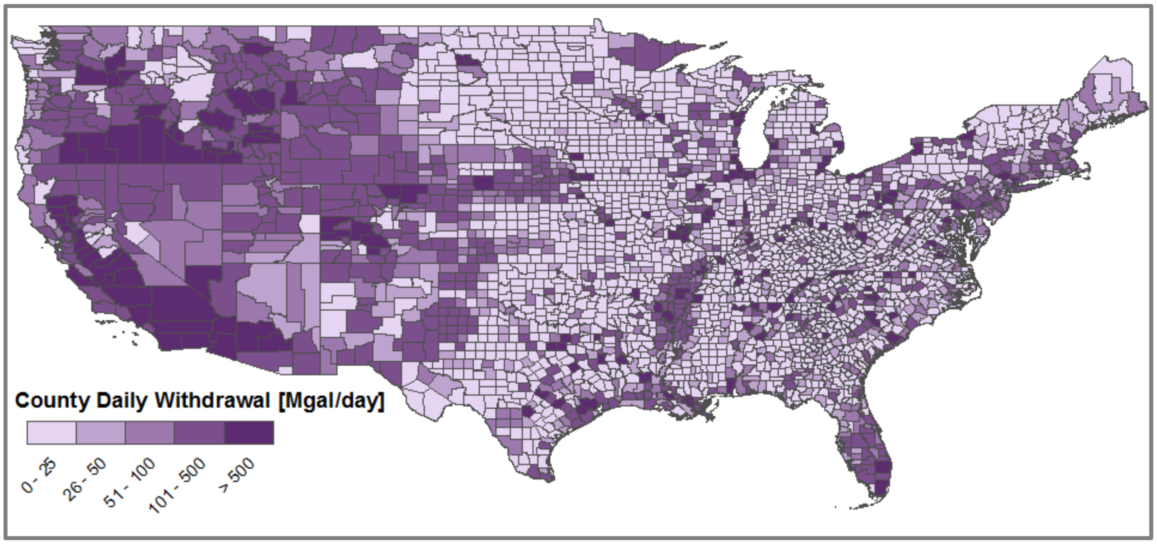

Figure 3-1 Mean daily fresh water withdrawal from all sources by county, 2001-2005 in Mgal/day

Additionally, the USGS provides a vector file of the national hydrologic regions classified by a HUC which was downloaded to be the analysis boundary areas. The boundaries are available as shapefiles which can be viewed in ArcGIS. The 4-digit and 10-digit regions were used to explore scaling when calculating WSI at a national level. Figure 3-2 shows the difference between 4-digit and 10-digit HUC boundaries. The 10-digit HUC boundary dataset provides the downstream 10-digit HUC as an attribute, which is used during the routing calculations to determine upstream flow, as discussed in Section 3.4.

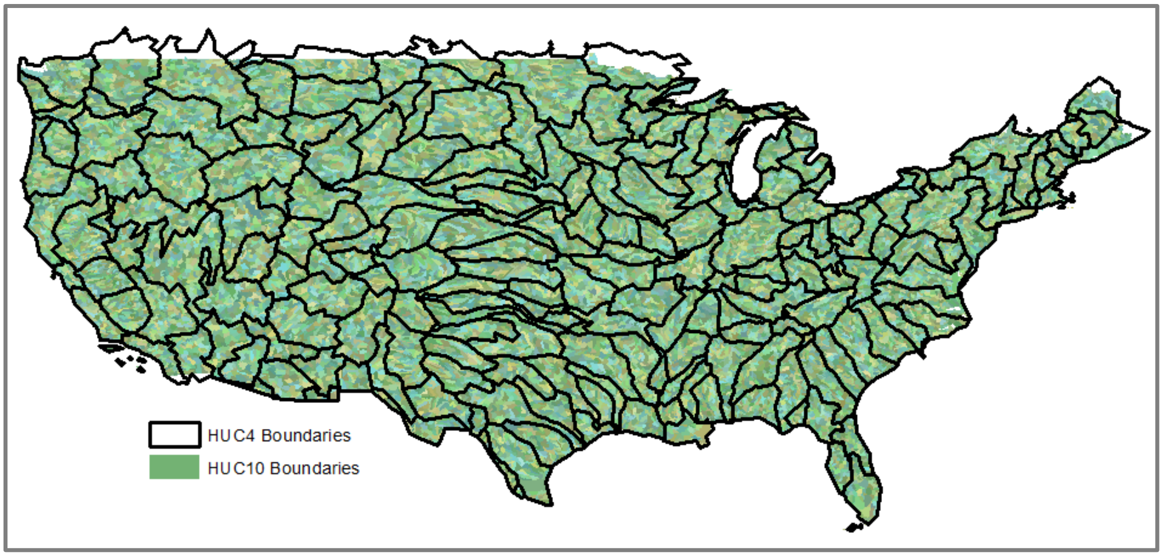

Figure 3-2 Comparison of 10-digit HUC boundaries and 4-digit HUC boundaries

3.3.2 Simulated National Datasets

Beyond the downloaded datasets, simulated total runoff was generated using the Variable Infiltration Capacity (VIC) model at 1/8th degree resolution for the contiguous United States. The VIC model, a semi-distributed hydrologic and land surface model, takes time series inputs (daily precipitation, temperature, wind speed) and parameters (landcover, soil) to solve a complete water and energy budget for each individual grid cell (Liang et al. 1994; Cherkauer et al. 1999). The model outputs both daily surface and subsurface runoff over the grid cell as a depth per time that can be routed at the watershed level to produce streamflow. The VIC simulated climatology of total annual runoff (surface and subsurface) averaged from 1950-1999 was used as the locally generated runoff, R_i, value in the WSI calculation and is shown in Figure 3-3. The model set-up that was calibrated and evaluated by Sabo et al. (2010) was used for this application and is described briefly here.

Using a combination of 7 naturalized and 5 observed streamflow gauging sites minimally impacted by dams and reservoirs, the model was calibrated for 6 major river basins: Columbia, Colorado, Missouri, Arkansas, Ohio and Upper Mississippi. The model was calibrated for a period of about 10 years ranging from 1950 to 1999; however, based on availability of naturalized or observed streamflow records, the 10 year calibrations do not necessarily match for the 12 sites. Overestimates in streamflow were observed for wet regions such as the Pacific Northwest (12.96%) and Upper Mississippi (15.8%), whereas underestimates were more recurrent in arid regions such as the Colorado (-8.98%) and Missouri (-7.4%), river basins where hydrographs are driven by snowmelt. The biggest outlier was the Arkansas basin with overestimation of streamflow by 32%, most likely due to poorly documented water withdrawals and diversions. The calibrated parameters for the other basins were chosen from one of these six river basins with similar hydroclimatological conditions (Sabo et al., 2010).

The time period of the average county-level withdrawals (2000-2005) differs from the time period used to generate the water supply climatology from the VIC model (1950-1999). It was considered important to use the most up-to-date summary of current water use within the US, assuming that temporal variability in water withdrawals is greater than variability in water supply. In some locations this choice will introduce error where the annual average water supply for 2000-2005 was substantially different than the 1950-1999 climatology.

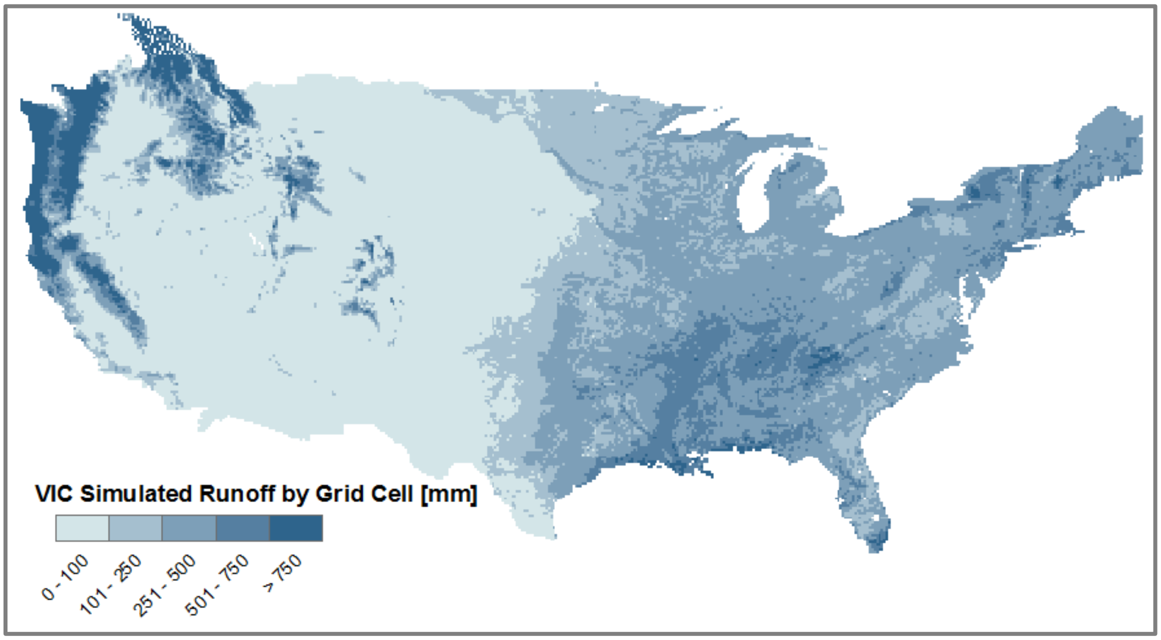

Figure 3-3 VIC simulated average annual total runoff (1950-1999) in mm/year

3.4 Rescaling the Datasets

The water withdrawal dataset is a shapefile with values corresponding to county boundaries and the runoff dataset is a raster grid at 1/8th degree cell size. In order to find WSI values at 10-digit HUC boundaries, the input datasets were rescaled to 10-digit HUC boundaries so that all inputs are on the same scale and in the same units.

3.4.1 Water Withdrawal Datasets Conversion

As described above, the 2005 Water Use Table, originally by county, was joined to a shapefile of county boundaries. Each polygon vector dataset, total water withdrawal and surface water withdrawal, was converted to a 0.125 degree latitude by longitude resolution raster dataset of withdrawal per unit area with the value from the following ratio:

$$W_n = \frac{W_c}{A_c} \qquad \text{Equation 3-3}$$

where W_c is the county withdrawal (Mgal/day) and A_c is the county area (mi^2). Next a new raster dataset of withdrawal volume for each grid cell was created as follows:

$$W_g = W_n * A_g * CF \qquad \text{Equation 3-4}$$

where A_g is the grid cell area (km^2) and CF is a conversion factor to convert from Mgal/day/mi^2 to m^3/grid cell/year.

Zonal statistics, in this case the sum, of the grid cell values within a 10-digit HUC boundary were used to generate a final raster dataset of each watershed's annual withdrawal in m^3/year. This was converted to a text file and joined to the master table used for the routing and WSI programs written for this analysis. The resulting table has an estimated total water withdrawal volume (m^3/year) and surface water withdrawal volume (m^3/year) for every 10-digit HUC in the contiguous United States. The process was repeated for additional water withdrawal datasets to investigate stress due to ground water, irrigation, and public supply withdrawals.

3.4.2 Total Runoff Datasets

The output from the VIC model is depth of total runoff per grid cell. A new 0.125 degree volume of total runoff raster was calculated as:

$$R_i = R_g * A_g * CF \qquad \text{Equation 3-5}$$

where R_g is the grid cell runoff (mm/year), A_g is the grid cell area (km^2), and CF is a conversion factor to convert from mm* km^2/year to m^3/year. Zonal statistics, the sum in this case, of the grid cells within a 10-digit HUC boundary was generated, converted to a text file and joined to the master table to provide an estimate of the total volume of runoff (m^3/year) generated within each 10-digit HUC boundary.

3.5 Watershed Routing Model

Because the WSI supply value is dependent on the discharge of upstream watersheds, a method was created to generate an ordered list of 10-digit HUCs so that upstream watersheds have a higher rank than downstream watersheds. WSI calculations can then proceed from higher to lower ranked watersheds. Using the USGS attribute table connected to the hydrologic regions shapefile, which included the downstream 10-digit HUC ID that each watershed discharges into, the following methodology was used, as illustrated in Figure 3-4:

1. Each 10-digit HUC is initially assigned a rank of 1.
2. The ID for the first 10-digit HUC is assigned as the “current HUC.”

3. An iterative loop calls a function to search the table to find the upstream watersheds of the current HUC.
4. The function, a recursive program, searches each row of the table for an instance when the current HUC is listed in the downstream column, meaning the 10-digit HUC in that row is immediately upstream of the current HUC.
5. The following Boolean operations determine how to proceed:
    a. If the upstream HUC has a greater rank than the current HUC, then upstream rank is not changed, and the search moves to the next row.
    b. If the upstream HUC has an equal or lower rank, then the upstream rank is changed to 1 greater than the current HUC's rank, and the recursive function starts over at #4 reassigning the "current HUC" as the upstream HUC ID.
6. The recursive function finds all upstream HUCs increasing the ranks so that the stream network is ordered where the most upstream HUC has the greatest rank. The recursive loop ends once the entire river network upstream of the original current HUC has been checked by the Boolean operation. Figure 3-4 depicts the program logic of the recursive function.
7. Once the recursive loop has ended, the iterative loop starts back at #2 for the next HUC ID listed in the table. The iterative loop ends once the last column has been checked.
8. The table is ordered by highest rank so that discharge and WSI of all upstream HUCs are calculated before the downstream HUCs.

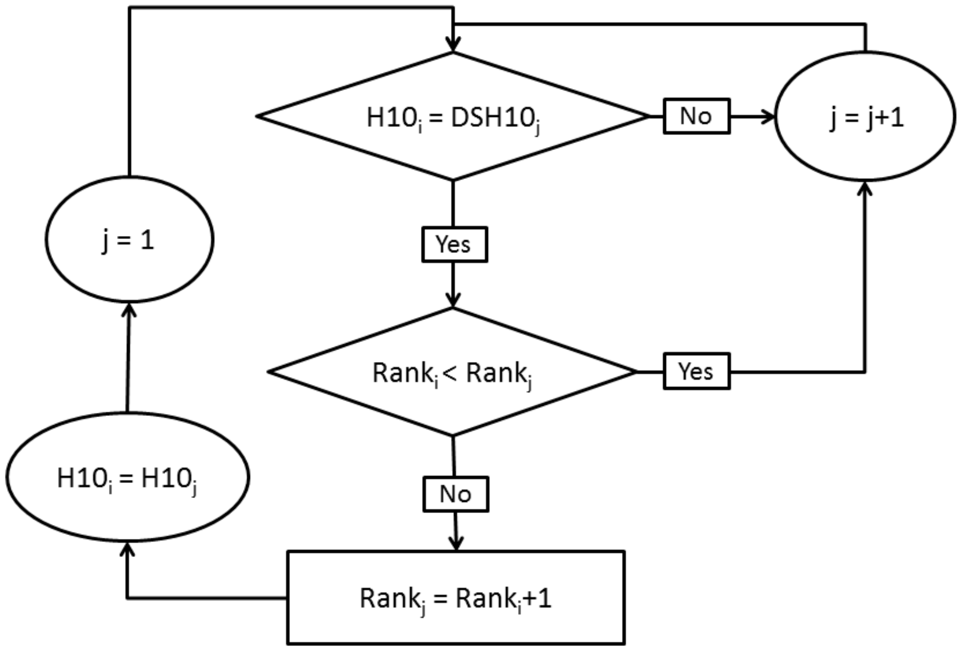

Figure 3-4 Schematic of the recursive function where $H10_i$ is the current HUC; $DSH10_j$ is the downstream HUC listed in the record currently being checked, $H10_j$; i the identifier for the current HUC row; j is the counter for the loop and identifier for the upstream HUC row; and Rank is the order of the river network moving upstream

By sorting the table so that the most upstream HUCs are first, the discharges will already be calculated for streamflow into the downstream watersheds. Using the streamflow and runoff, WSI is calculated by equation 3-1. In addition, water stress from different sectors is calculated by substituting the different withdrawal categories for W_i to find fraction of water stress caused by irrigation, public supply, groundwater and surface water withdrawals. The fractional water stress associated with each sector is then calculated as:

$$Fwsi_{A,i} = \frac{WSI_{A,i}}{WSI_{total,i}} \qquad \text{Equation 3-6}$$

where $WSI_{A,i}$ refers to the water stress index associated with a type of water withdrawal (irrigation, public supply, surface water, or ground water).

CHAPTER 4. NATIONAL WATER STRESS INDEX

4.1 10-Digit HUC Water Stress Calculations

The map in Figure 4-1 shows water stress index (WSI) values by 10-digit HUC for the contiguous United States. WSI is calculated as demand over supply, where the demand is the average annual USGS county withdrawal data from 2001-2005 and supply is the average annual VIC simulated runoff using precipitation data from 1950-1999, as described in Chapter 3. WSI values over 0.4 are considered to be an indicator of water stress (Alcama et al. 2003, Vorosmarty et al. 2000, Oki and Kanae 2001). It can be seen from Figure 4-1 that there are large areas experiencing water stress throughout the US, particularly in the West. WSI values greater than 1, indicating a deficit, can be due to large water relocation projects transporting supply between watersheds. More likely, heavy groundwater pumping is the reason. Groundwater withdrawals are considered in the numerator of WSI. The VIC simulated runoff includes renewable supply from both surface and subsurface flow; however, water mined from deep aquifers is not included in this value. WSI values exceeding 1 can be seen in both the eastern and western US.

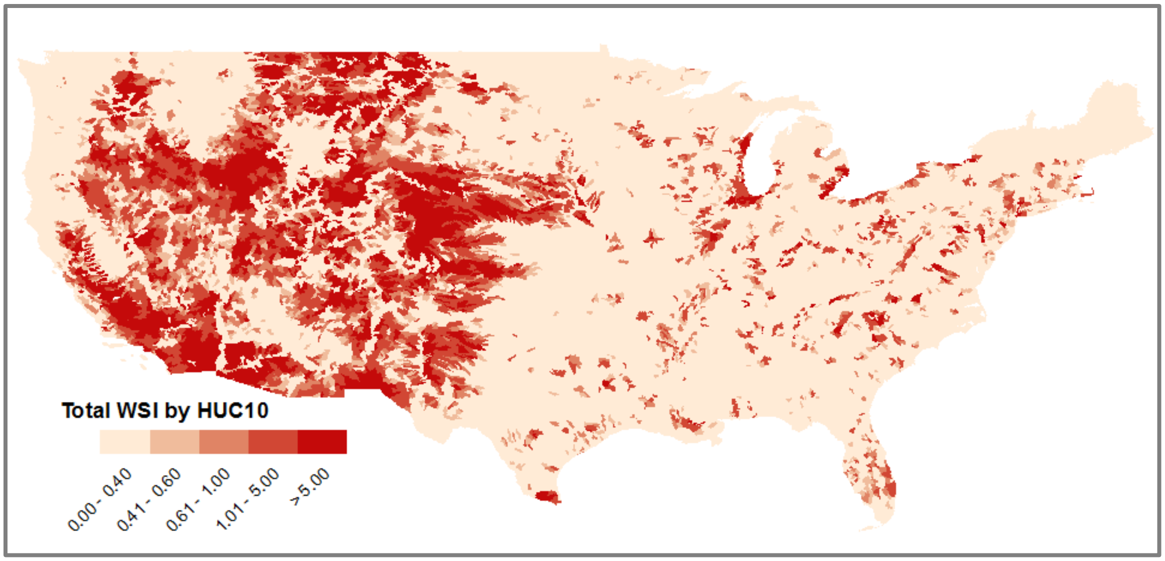

Figure 4-1 Total water stress index by 10-digit HUC boundaries

4.1.1 East vs West Water Stress Index

When analyzing the two components of WSI, either low supply or high demand could be the influencing factor for high WSI values. Figure 4-2 shows total runoff by 10-digit HUC boundaries in m^3, which as the denominator creates high WSI when total runoff has low values. High WSI in the West (Figure 4-1) is most likely driven by low supply (Figure 4-2).

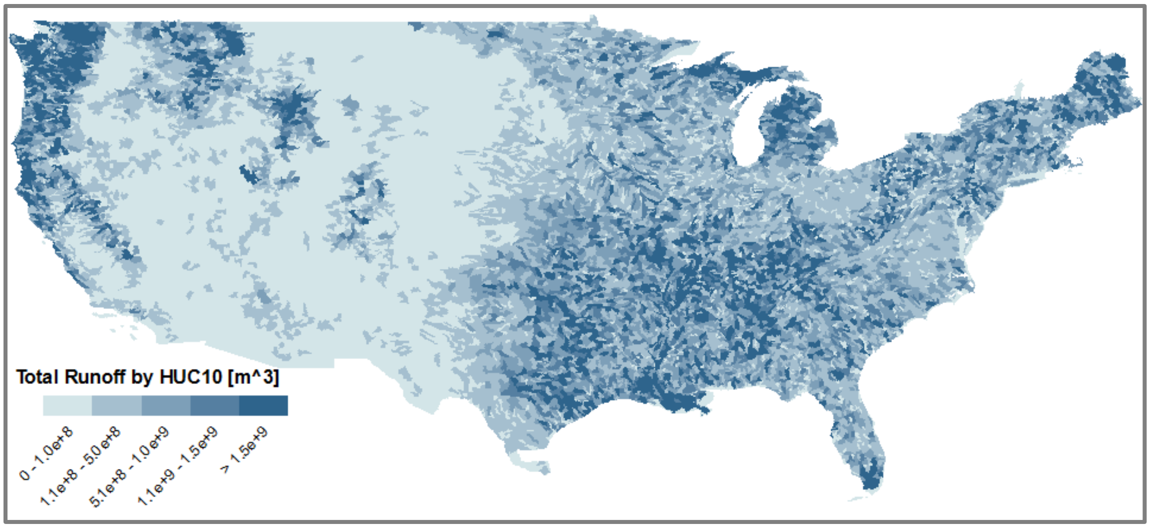

Figure 4-2 Total runoff by 10-digit HUC boundaries in m^3

Conversely, a high numerator, which in this case is demand, can generate high WSI. Figure 4-3 shows total withdrawal by 10-digit HUC boundaries in m^3. The areas of high demand (Figure 4-3) align with the areas of high WSI (Figure 4-1) in the East, reinforcing the idea that WSI is demand driven in the East.

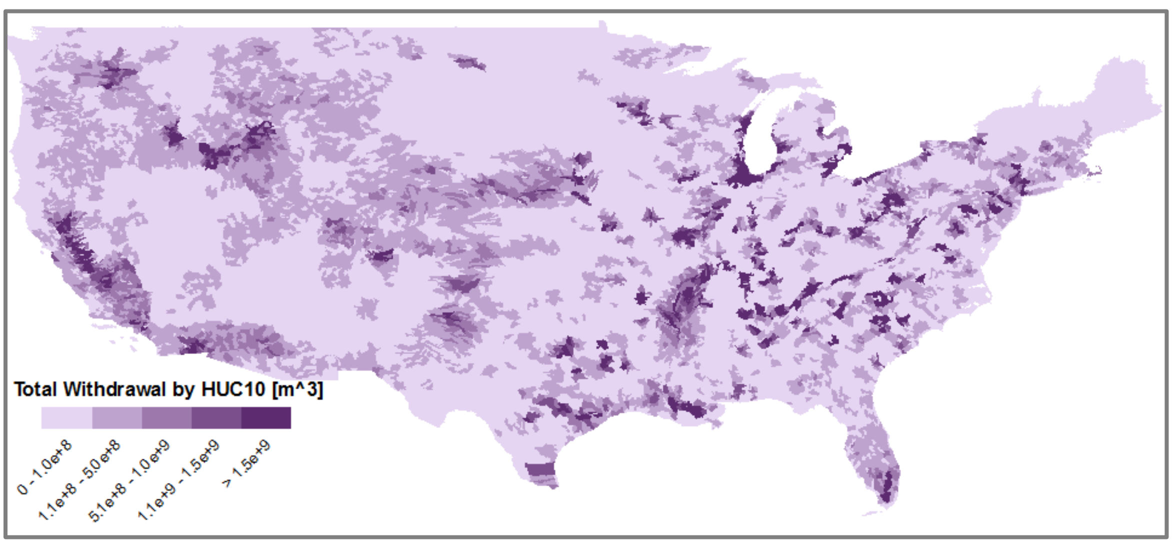

Figure 4-3 Total withdrawal by 10-digit HUC boundaries in m^3

4.1.2 Scaling

The influence of spatial scale on WSI is explored by using 4-digit and 10-digit HUC boundaries. Figure4-4 shows the WSI values calculated at 4-digit HUC resolution by Sabo et al. (2010) by directly routing discharge between 4-digit HUCs and using the same VIC dataset for water supply. The 10-digit HUC analysis shown in Figure 4-1 overall calculates higher WSI values in the West than that performed for 4-digit HUCs. This is because water withdrawals are concentrated into much smaller watersheds, where the impact on locally-generated runoff can more clearly be seen. In addition, much more spatial heterogeneity is seen in both the East and West in the 10-digit HUC analysis. The WSI values in the East are shown as high in small areas at the watershed level. While the 4-digit HUC WSI values in the East are lower covering a larger area.

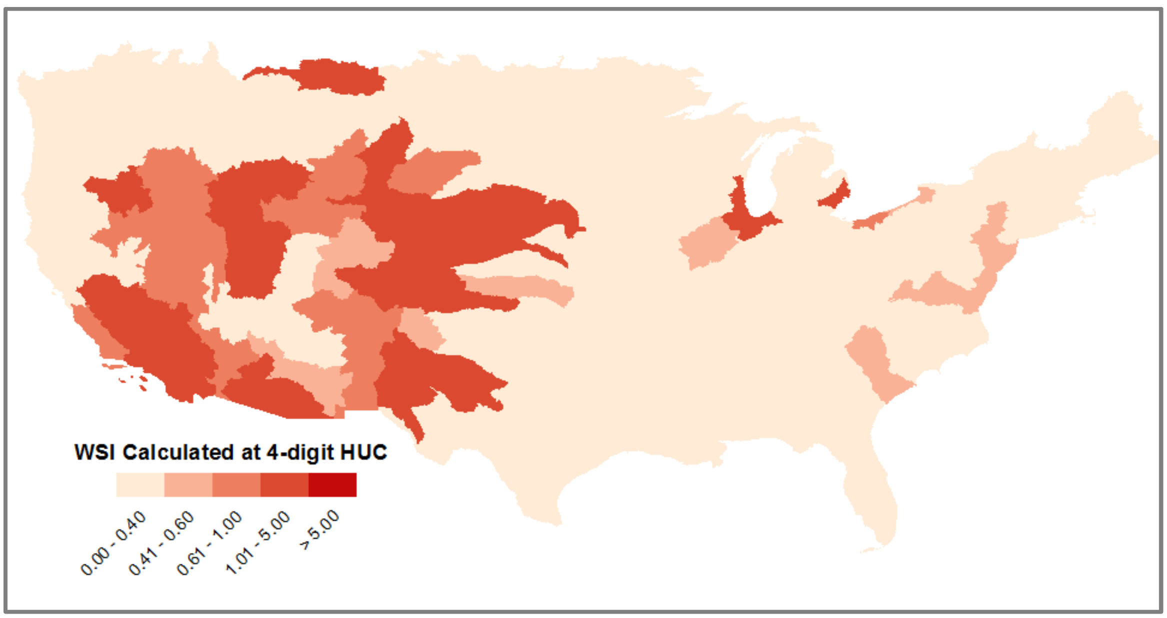

Figure 4-4 WSI calculated at 4-digit HUC boundaries (Sabo et al, 2010)

The 10-digit HUC WSI values averaged within a 4-digit HUC are shown in Figure 4-5. Averaging reduces the extreme WSI values seen in Figure 4-1, but not to the same extent as the original low resolution calculation. In addition, the scattered occurrence of water stress in the eastern US is not as well captured by the averaged dataset, than by the 4-digit HUC calculation method.

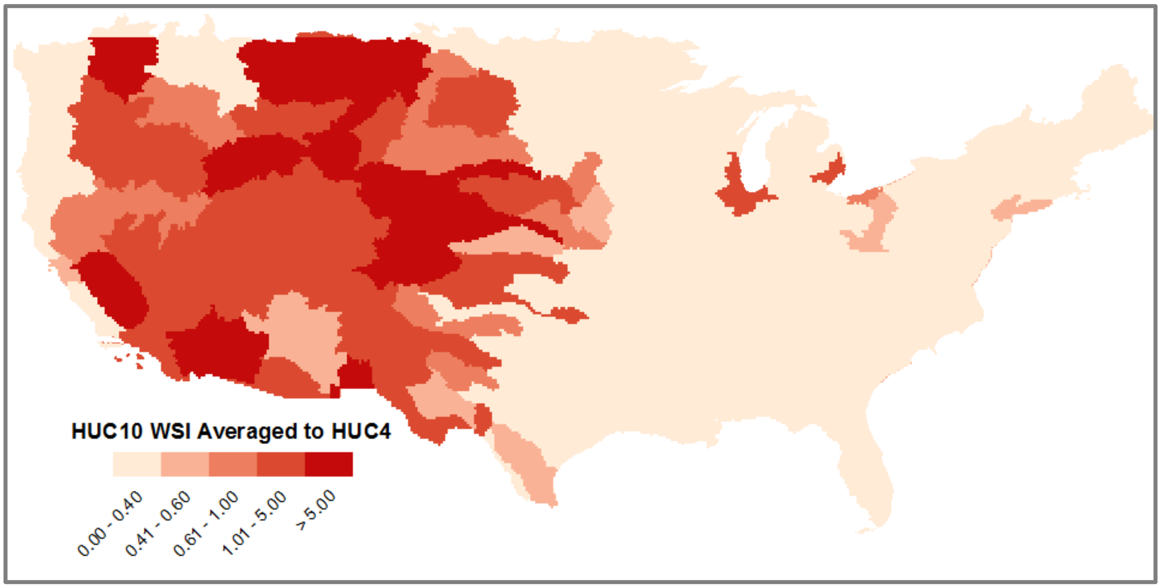

Figure 4-5 WSI calculated at 10-digit HUC resolution averaged over 4-digit HUC boundaries

4.2 Regional Water Stress Patterns

In order to explore the role of demand and supply in controlling water stress, this section discusses the results from using public supply, irrigation, ground water and surface water withdrawal data to calculate WSI.

4.2.1 Demand Sources

The extent to which water stress can be attributed to demand is explored in this section by calculating water stress caused by different demand sectors at the 10-digit HUC level. Figure 4-6 illustrates the water stress calculated using just freshwater withdrawals for irrigated agriculture. Large areas of high water stress emerge in the arid west where crop water needs are supplemented by irrigation systems pulling from both surface water and ground water sources. The irrigation WSI in the West matches closely with total WSI in that area and is almost nonexistent in the East, with the exception of southern Florida and along the Mississippi River in Arkansas.

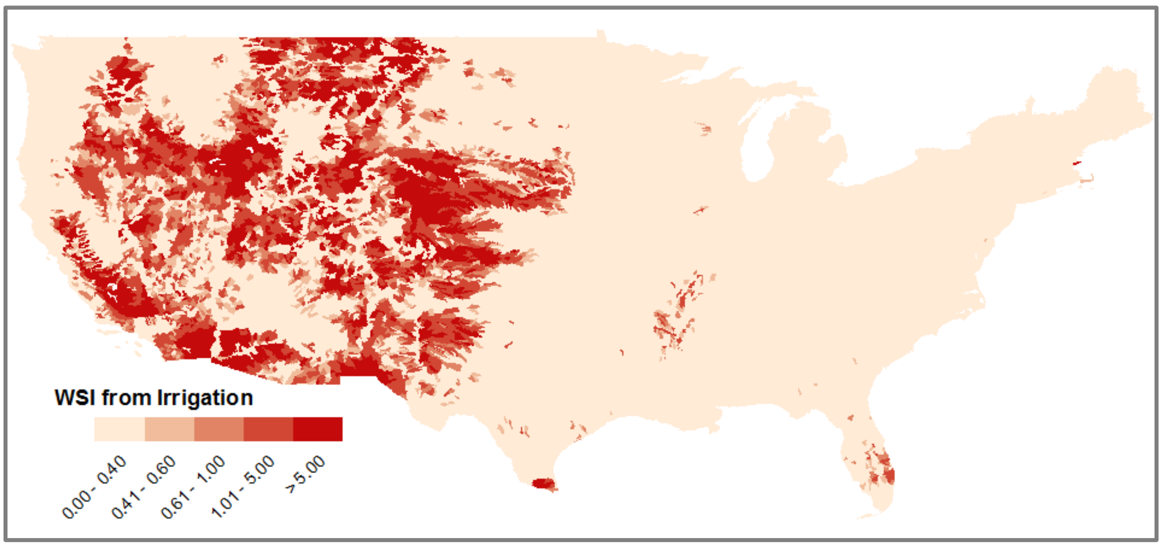

Figure 4-6 WSI due to irrigation withdrawals calculated at 10-digit HUC boundaries

Public supply was analyzed to investigate the hypothesis that large population centers in the East cause water stress when there is competition between states and users. Figure 4-7 shows the public supply WSI and indicates that there are patches of high demand in the East matching areas of high total WSI. Domestic, industrial, or other types of users are considered together if drawing from a public system. Even though it is not possible to separate domestic users alone, the withdrawal values are still appropriate because it indicates stress on the water supply system in and immediately around large population centers, which often serve as centers of industry as well.

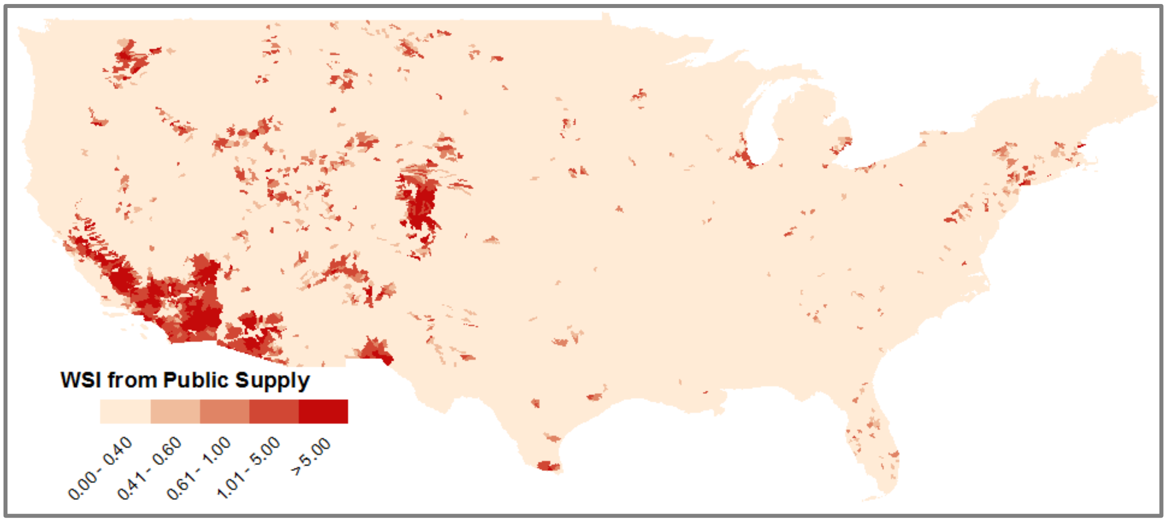

Figure 4-7 WSI due to public supply withdrawals calculated at 10-digit HUC boundaries

Breaking down the different types of WSI into fractions of the total WSI, we can show which users are contributing the most to water stress. The fraction of WSI from each demand sector is shown in Figures 4-8 and Figure 4-9. The fraction of WSI is unbiased to the total WSI values. For example, a watershed can have a relatively low total WSI value and public supply value but could have a high fraction of WSI from public supply. Areas of particular concern occur when there is a combination of high total WSI (Figure 4-1) and split types of demand (Figures 4-8 and 4-9), such as Florida. The high WSI alone is a concern, but adding to that the competition between agricultural, industrial, and municipal users makes managing the issue more complicated.

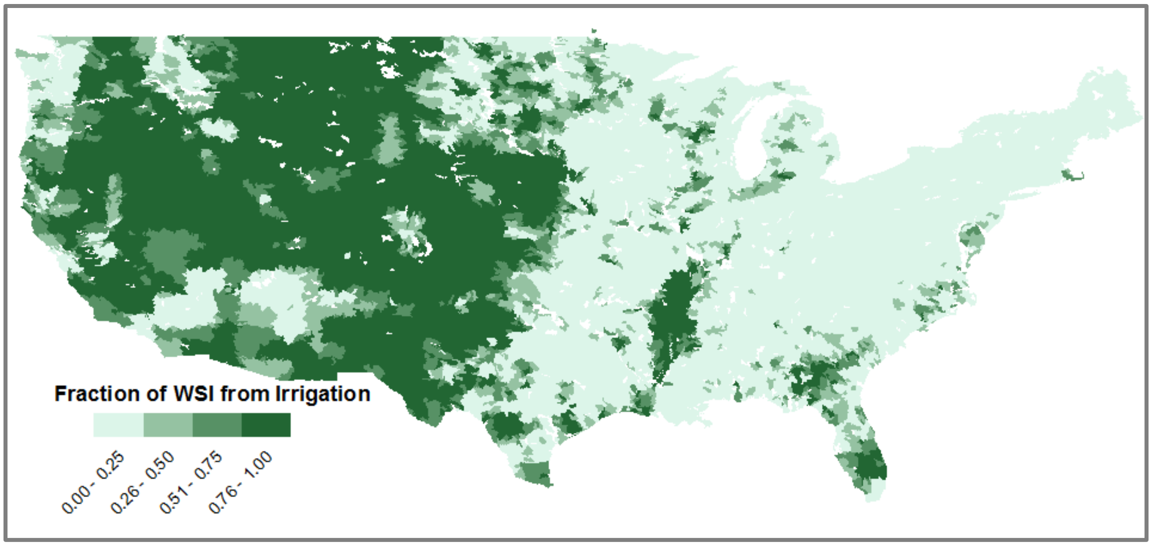

Figure 4-8 Fraction of WSI due to irrigation withdrawals calculated at 10-digit HUC boundaries

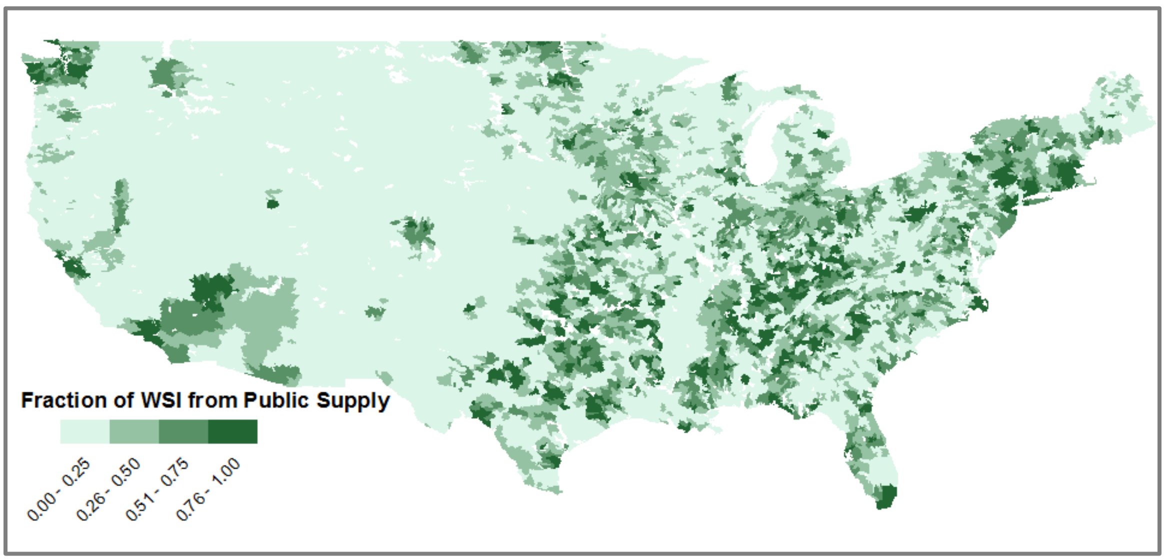

Figure 4-9 Fraction of WSI due to public supply withdrawals calculated at 10-digit HUC boundaries

Figures 4-8 and 4-9 illustrate a national scale pattern of irrigation-induced water stress in the West and public/industrial use in the East.

Population density and major rivers are overlaid onto the 10-digit HUC WSI values in Figure 4-10. This shows that the high WSI values in the East mostly correspond to a population center or centers. However, in the West large areas of high WSI are not near large cities, with the exception of California.

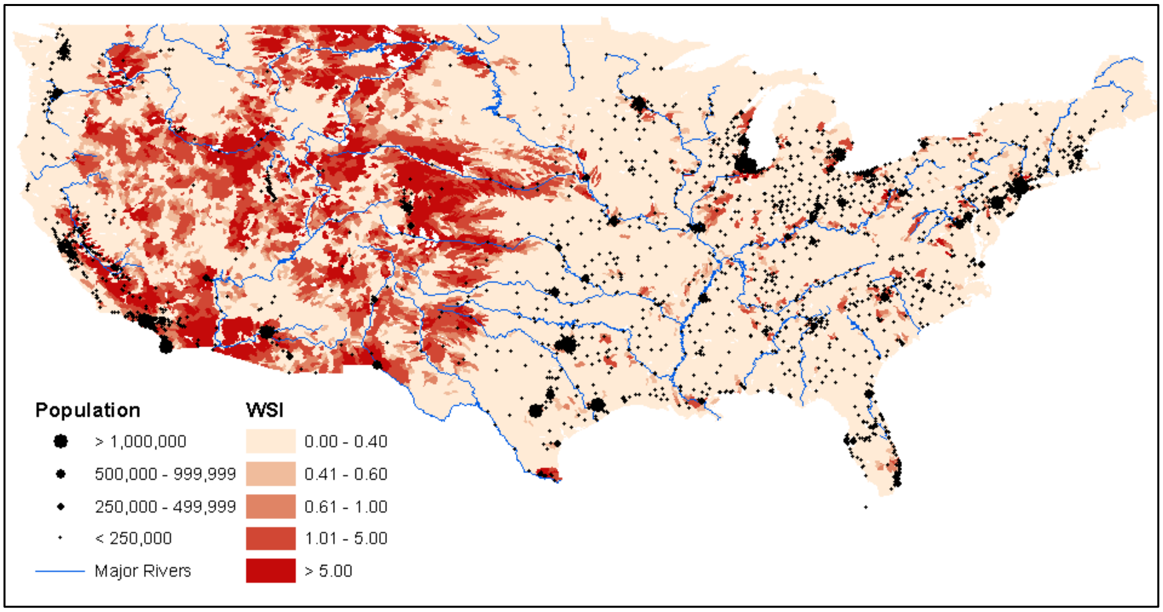

Figure 4-10 Total water stress index by 10-digit HUC boundaries compared with population density and major rivers

4.2.2 Supply Sources

Analysis using a similar breakdown between water withdrawals from surface water sources or ground water sources is discussed in this section. Overall, stress due to surface water withdrawals appears in both the East and West (Figure 4-11), with high water stress due to ground water withdrawals predominately occurring in the West with the exception of a pocket in Florida and in Arkansas (Figure 4-12).

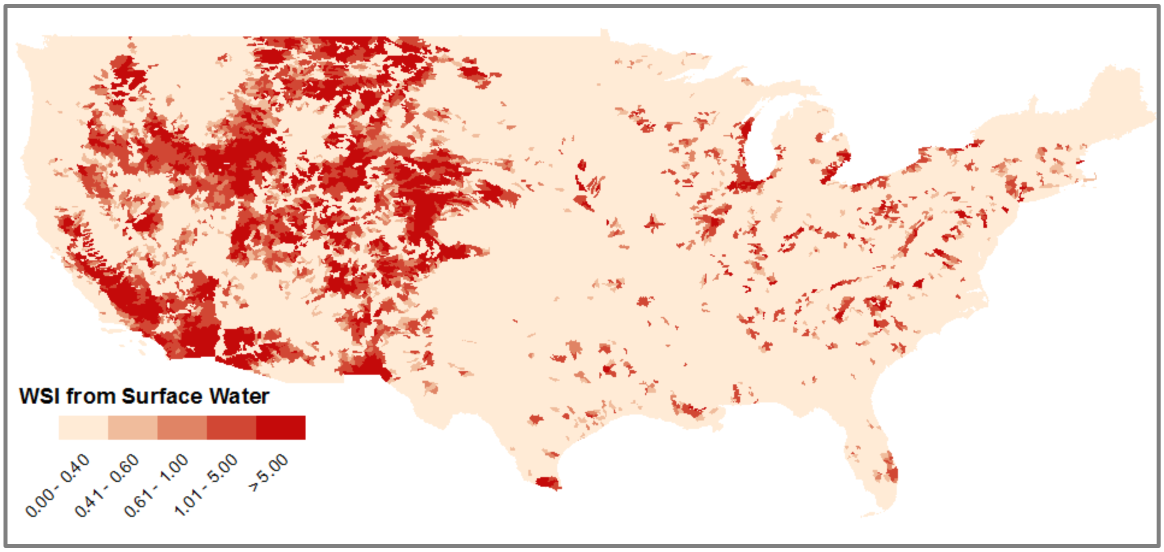

Figure 4-11 WSI due to surface water withdrawals calculated at 10-digit HUC boundaries

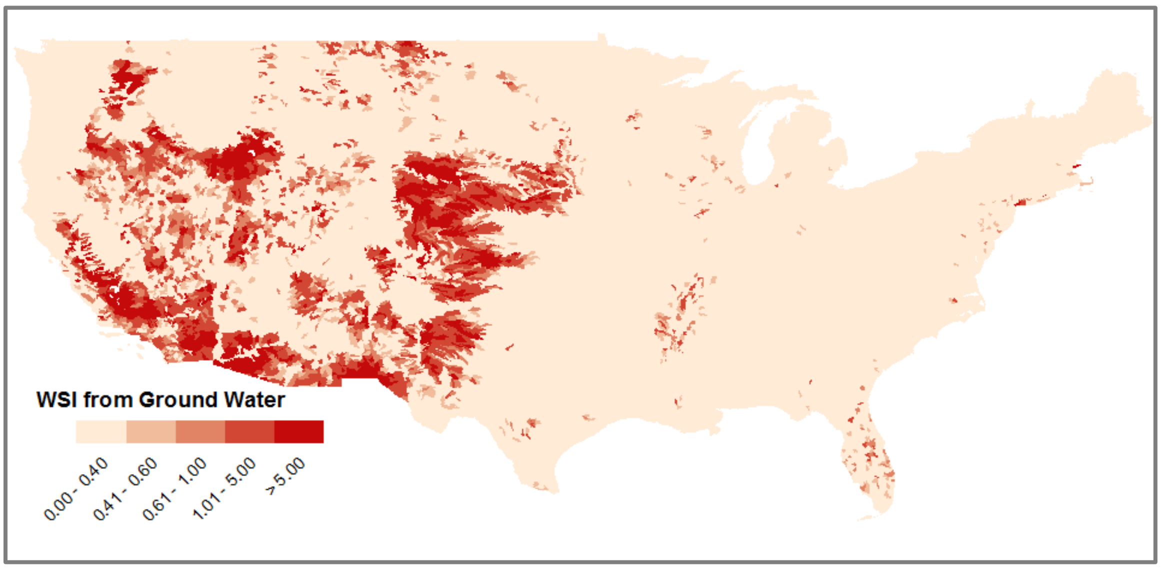

Figure 4-12 WSI due to ground water withdrawals calculated at 10-digit HUC boundaries

The fraction of WSI due to either surface water or ground water withdrawals spans from east to west with no clear division along the 100th meridian (Figures 4-13 and 4-14).

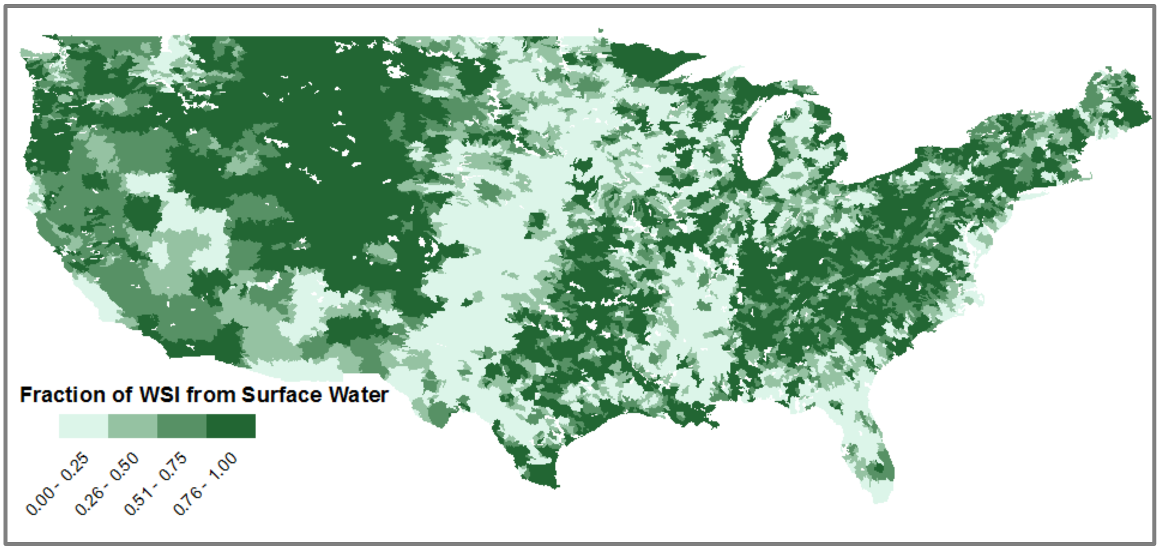

Figure 4-13 Fraction of total WSI due to surface water withdrawals calculated at 10-digit HUC boundaries

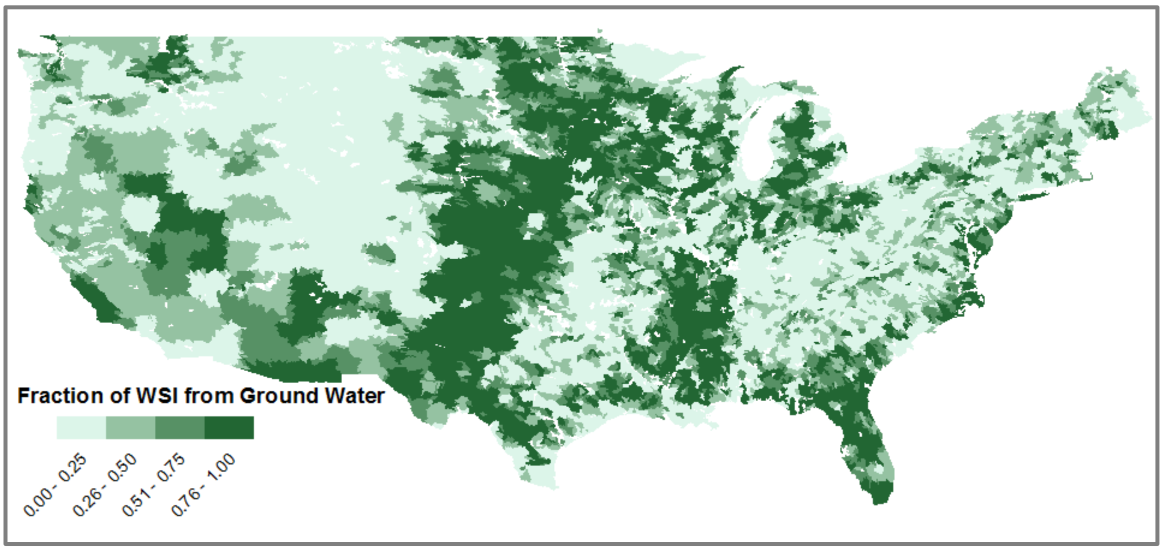

Figure 4-14 Fraction of total WSI due to ground water withdrawals calculated at 10-digit HUC boundaries

Considering sources of water, areas of concern are where there is high WSI and greater than 75% of the WSI from a single supply source. For example, West Texas has high WSI mostly from ground water. Pulling unsustainable amounts of water in general is concerning, but when it comes from a single source it can put a lot of strain on the ecosystem or aquifer.

4.3 Longitudinal Analysis of Water Stress Index

In order to see the regional differences in water stress across the contiguous United States, the 95th percentile values for WSI were averaged by longitudinal sections as shown in Figure 4-15. The highest 5% of values were excluded from the average because the range of WSI vales was better captured without the outliers. The graph shows that average total WSI is much greater in the West than in the East.

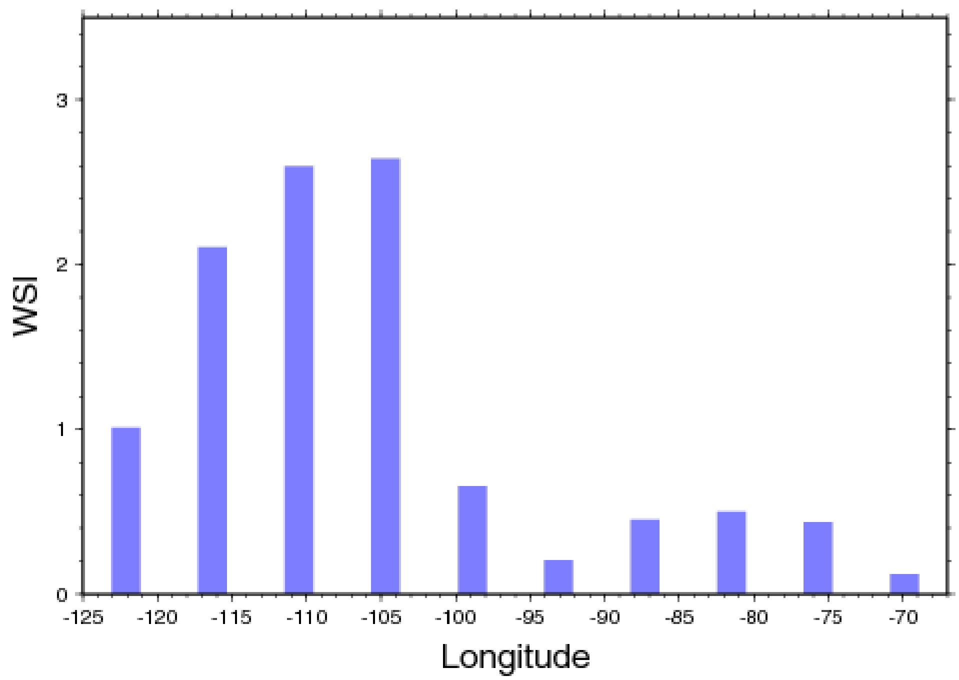

Figure 4-15 Longitudinal average of the 95th percentile of total WSI

Performing the same longitudinal averages for the different types of users, Figure 4-16 and Figure 4-17 show the average WSI of the 95th percentile and its fraction of total WSI for irrigation and public supply, respectively.

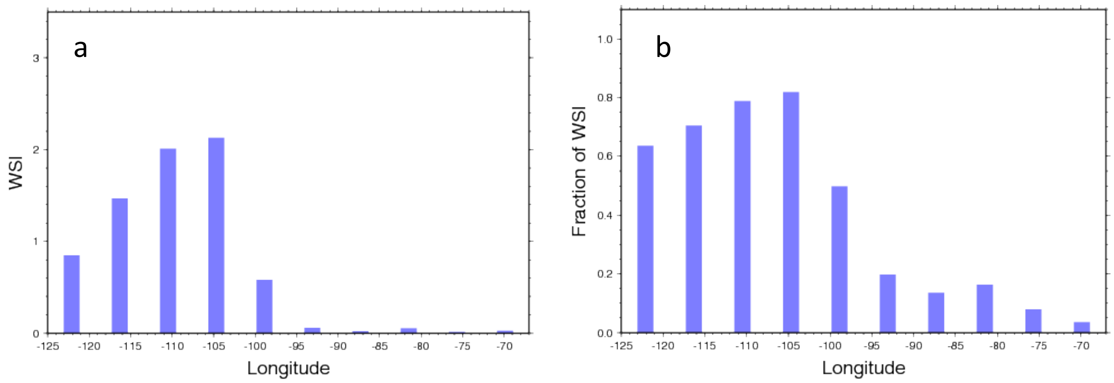

Figure 4-16 Longitudinal average of a) WSI from irrigation of the 95th percentile and b) fraction of WSI due to irrigation

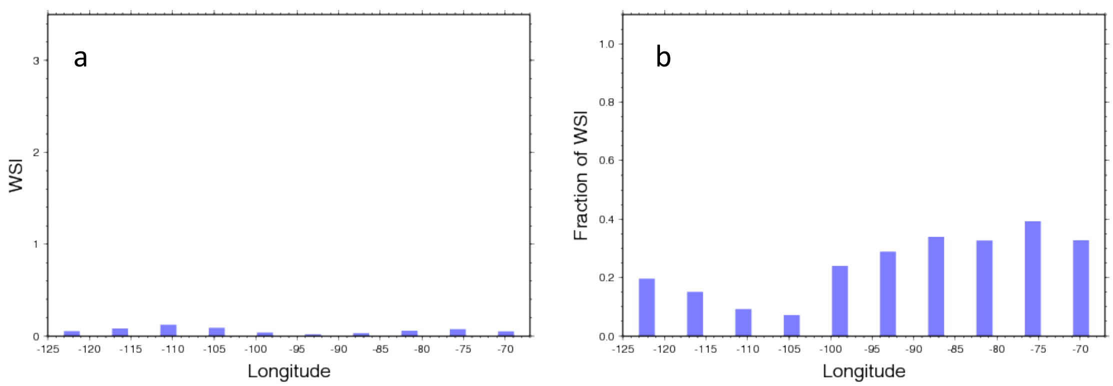

Figure 4-17 Longitudinal average of a) WSI from public supply of the 95th percentile and b) fraction of WSI due to public supply

WSI due to irrigation is both higher and dominates a higher fraction of the total WSI in the West (Figure 4-16). WSI due to public supply on the other hand does not present any concern when looking at the average (Figure 4-17a) because high values around cities are minimized due to large areas of low public supply WSI. However, in the East the average fraction of WSI due to public supply ranges between 30-40%, reinforcing the idea that total WSI is more influenced by population centers in the East.

In the same analysis on types of supply, Figures 4-18 and 4-19 show the longitudinal average of WSI for the 95th percentile and its fraction of total WSI for surface water withdrawals and ground water withdrawals, respectively.

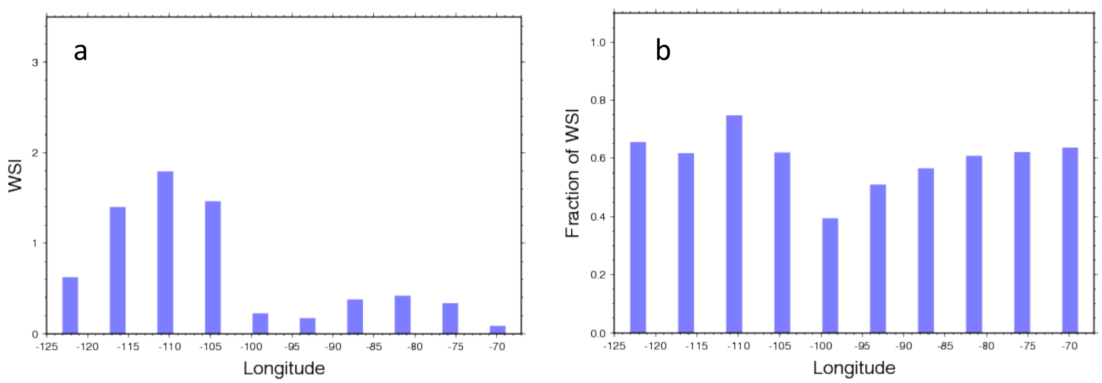

Figure 4-18 Longitudinal average of a) WSI from surface water withdrawals of the 95th percentile and b) fraction of WSI due to surface water withdrawals

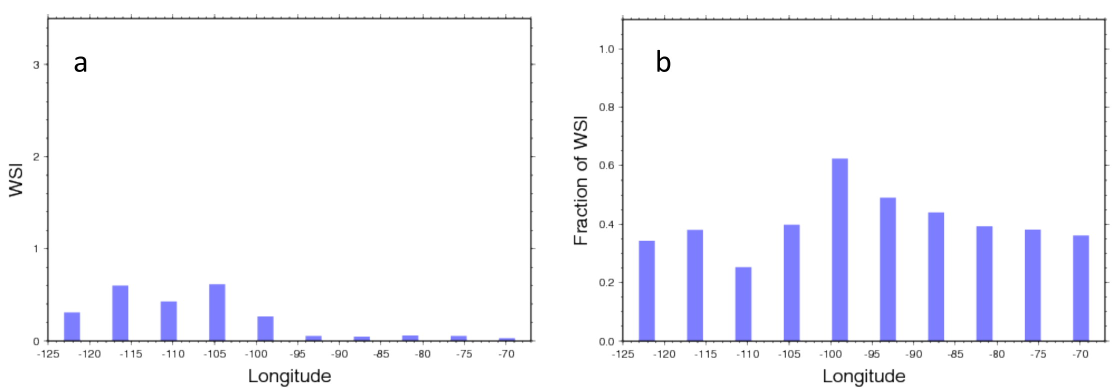

Figure 4-19 Longitudinal average of a) WSI from ground water withdrawals of the 95th percentile and b) fraction of WSI due to ground water withdrawals

The fraction of WSI due to surface water withdrawals is over 50% for both the East and West (Figure 4-18b), while the fraction of WSI due to ground water withdrawals only exceeds 50% along the 100th meridian (Figure 4-19b).

4.4 Discussion

As a metric for indicating unsustainable water usage, WSI is only useful when the values reflect accurate trade-offs between supply and demand. Due to the overlapping boundaries of natural ecological processes and human interactions on freshwater systems, determining the most appropriate scale and resolution to analyze the extent of water stress is vital. Due to spatial variability, calculations should be performed at the highest practical resolution to preserve effects of population centers. The figures in this chapter have shown that important information regarding stress around population centers is lost at low resolution. Therefore, calculations need to be at smaller local watershed levels when dense population aligns with water stress such as in the East. However, if data is reported at large county boundaries, such as in the West, effects of localized high withdrawal will not be seen, so larger scale WSI values are more appropriate.

CHAPTER 5. FACTORS INFLUENCING WATER STRESS IN THE EAST VS WEST

The next sections investigate the hypothesis that competition in the East between types of water users lead to high WSI values around population centers, driven by the demand part of the ratio. In contrast, water stress in the West is driven by the supply portion of the ratio and is less variable in spatial extent. For the comparison, a region from the Southeast, HUC 03 the South Atlantic Gulf Region, and the Southwest, HUCs 14 and 15 the Upper and Lower Colorado Rivers, were chosen to explore the differences in water stress and how it relates to human use patterns. Recall from Figure 2-1 the locations of these regions.

5.1 Boundaries Influencing Water Stress

The results of the water stress analysis will be discussed in context of geopolitical boundaries (cities, counties, states) and ecological boundaries (eco-regions). Due to variability in the scales, resolution, and data reporting, the dominant controls on water stress, the most appropriate boundaries to use for water stress calculation could differ across the United States.

5.1.1 Water Stress in the South Atlantic Gulf

Water Stress Index at the 10-digit HUC resolution was calculated across the region, as described in Chapter 4. In addition, the proportion of water stress from different sources (groundwater, surface water) and sectors (public supply, irrigation) is also explored. Across the South Atlantic Gulf there is relatively low WSI with the exception of high population centers and southern Florida, as shown in Figure 5-1. Average WSI is 0.34, ranging from 0 to 14.3. With the original, coarse scale WSI calculations (Figure 4-2), the high water stress around population centers was lost due to averaging over the larger areas. The next sections investigate the influences on spatial patterns of water stress in the South Atlantic Gulf.

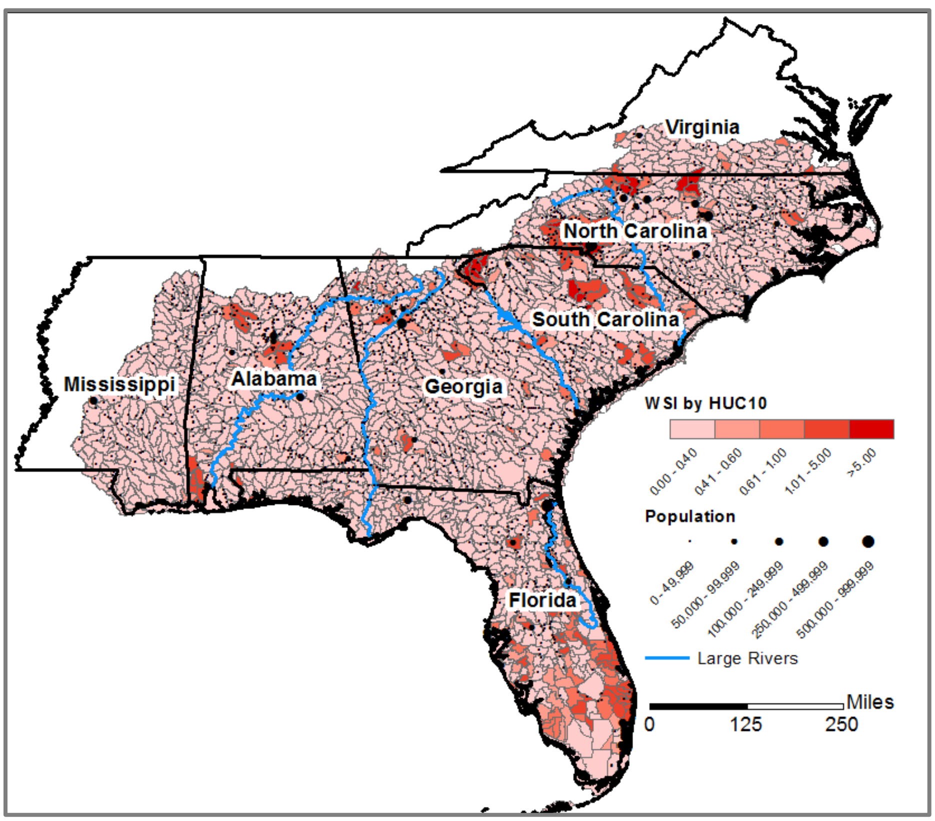

Figure 5-1 Water Stress Index across the South Atlantic Gulf by 10-digit HUC boundaries

5.1.1.1 Breakdown of Water Supply

The WSI in the northern portion of HUC 03 is from 50% or more of surface water use, while the WSI in the south and west (Mississippi) is from 50% or more of ground water use, as shown in Figure 5-2. The division between ground water and surface water stress coincides with the division between the Southeastern Mixed Forest and the Southern Appalachian Piedmont (Figure 2-2).

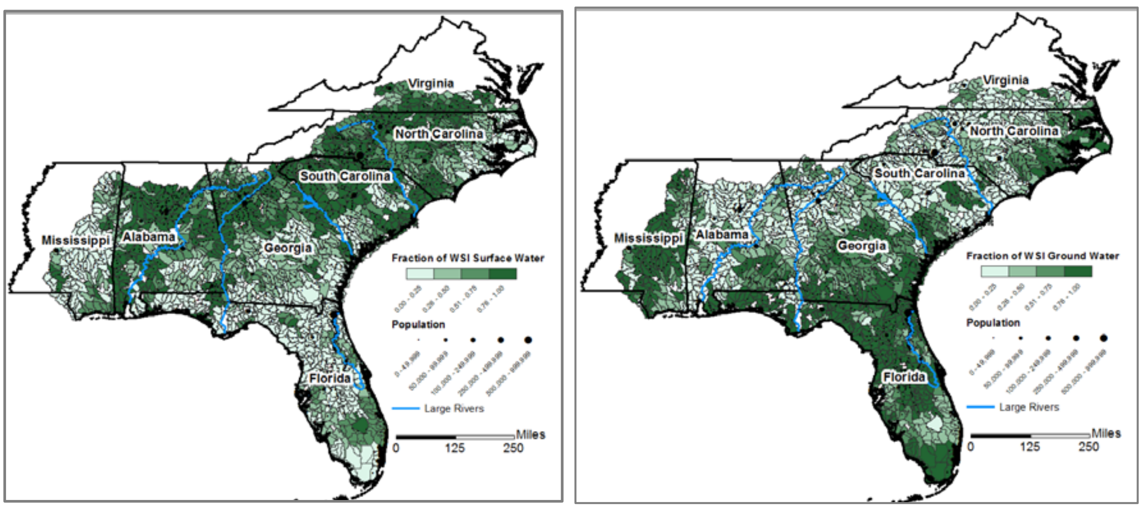

Figure 5-2 Fraction of WSI from a) surface water and b) ground water use in the South Atlantic Gulf Region

5.1.1.2 Breakdown of Water Demand

The fraction of WSI coming from public supply and irrigation are shown in Figure 5-3. Areas where the percentage of WSI from public supply is over 50% lie along the northern ridge of the region, as well as southern Florida. A high fraction of WSI due to public supply is situated at the headwaters of the ACT and ACF river systems, where lengthy water conflicts between states have taken place. Southern Georgia and most of Florida have most of the area where the percentage of WSI from irrigation is over 50%;

this is concerning considering the proportion of ground water used in the area (Figure 5-3b). Although high public supply is mostly in the Southeastern Mixed Forest region, there is not an exact correlation between surface water usage and public supply. Figure 5-3 shows more areas of mixed use, while Figure 5-2 shows very few areas of mixed supply.

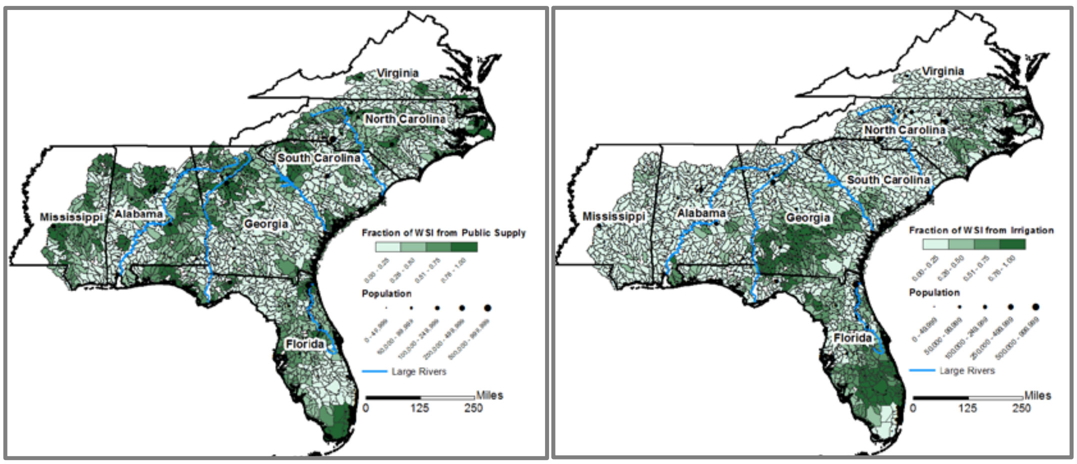

Figure 5-3 Fraction of WSI from a) public supply and b) irrigation in the South Atlantic Gulf Region

5.1.2 Water Stress in the Colorado River Basin

Water stress in the Colorado River Basin is generally high with areas of high stress not necessarily matching up with population centers, as shown in Figure 5-4. Average WSI in the region is 7.1, ranging from 0.03 to 86. The hypothesis that water stress in the West is driven by the supply portion of the ratio is investigated in the next sections.

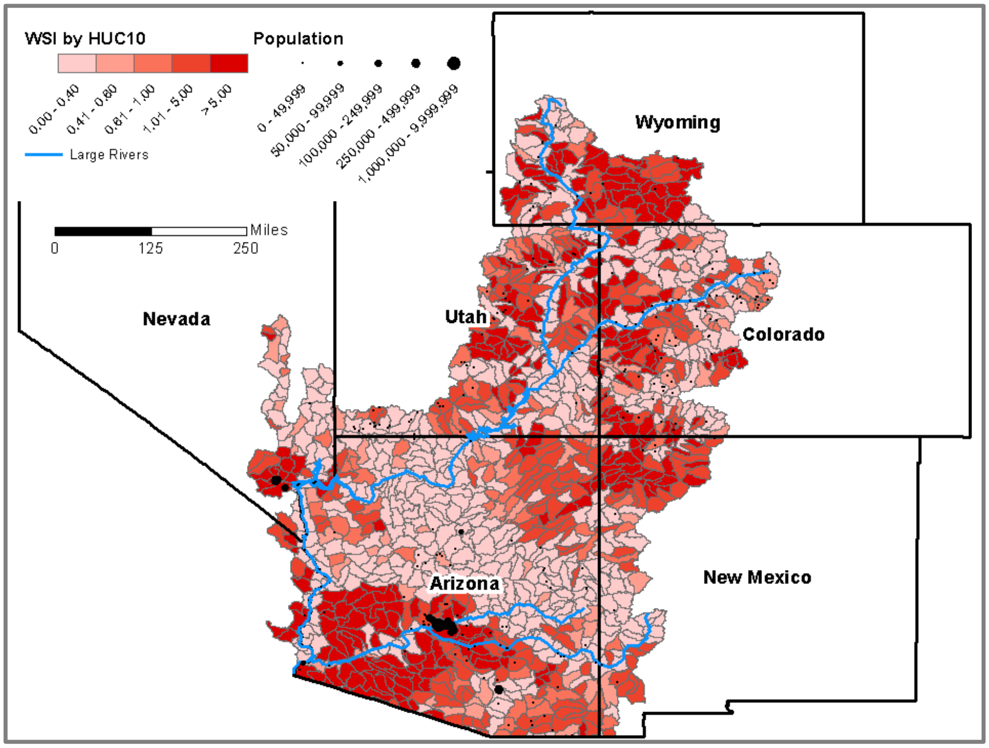

Figure 5-4 Water Stress Index in the Colorado River Basin by 10-digit HUC boundaries

5.1.2.1 Breakdown of Water Supply

WSI in Utah, Colorado and Wyoming is due almost exclusively to surface water withdrawals. Arizona, however, shows a mix between both surface water and ground water usage. The divisions in surface water and ground water use align with state boundaries rather than ecological regions. This is shown in Figure 5-5.

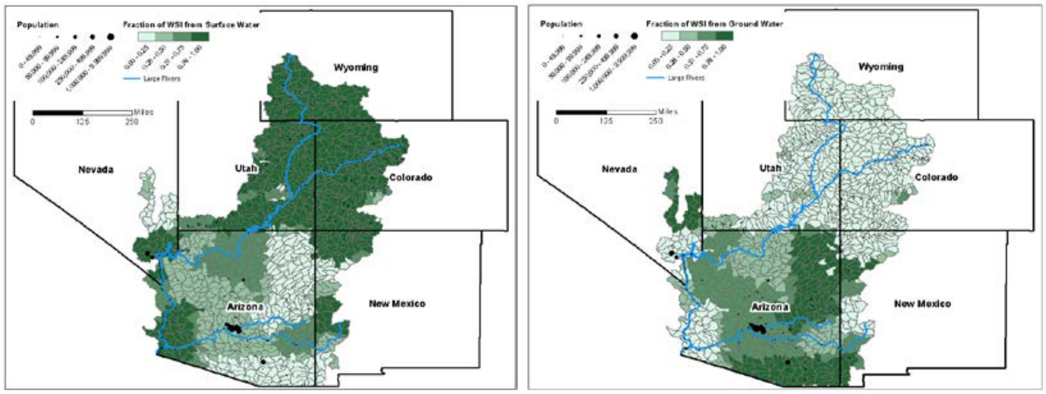

Figure 5-5 Fraction of WSI from a) surface water withdrawals and b) ground water withdrawals

5.1.2.2 Breakdown of Water Demand

A relatively small proportion of the water stress is due to the demand from the public supply sector, as seen in Figure 5-6. The distribution of the fraction of water stress from irrigation is high all over excluding north central Arizona.

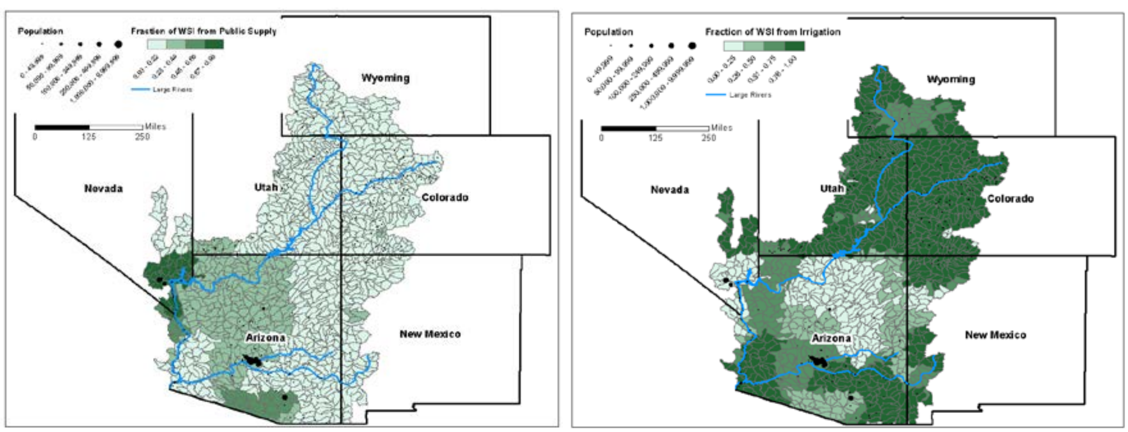

Figure 5-6 Fraction of WSI from a) public supply withdrawals and b) irrigation withdrawals

Water stress fractions align with geopolitical boundaries in the southwest, specifically county and state. Large county boundaries, the reporting scale for water withdrawals, control the values and variability for water stress index.

5.2 Population and Demand

One of the hypotheses being tested is that population centers are a controlling factor for the distribution of water stress in the Eastern United States, while climate is the controlling factor in the western United States. Recall from Chapter 4, the longitudinal plots of water stress moving east to west show that total WSI is almost three times greater in the West. However, if the causes of water stress are broken down into different demand categories, around 30-40% of water stress in the east is due to public demand while it is less than 20% in the west. As can be seen when comparing Figures 5-2 and 5-4, areas of high WSI are spatially discontinuous in the South Atlantic Region, and generally are near large population centers. In contrast, areas of high and low WSI are spatially connected in the Colorado River Basin, with many areas of high WSI distant from population centers.

To see if policy influences water stress, price was used as a potential indicator for regulation; essentially, is there a connection between low prices and high water stress. Therefore, published water prices were compared to per capita water withdrawals and local WSI. Because water price data is limited and provided by so many different sources, the published compiled water price chart for the 30 most populated cities in 2010 was chosen for the comparison (Walton, 2010). The cities are separated by longitude into East, West and Central locations and then the average monthly bill for a family of 4 using 150 gal/person/day was plotted versus the annual per capita withdrawal for public supply in the HUC corresponding to each city. Looking at the annual per capita withdrawal for public supply versus the average monthly bill for a family of 4 using 150 gal/person/day, Figure 5-7, there is no clear relationship between price and withdrawal rates. Santa Fe, NM has the most extreme water price increase in the dataset to try to decrease consumption. For the rates 50, 100, and 150 gal/person/day, the price goes from approximately $40 to $120 to $225, respectively. There is also no clear difference in the relationship between eastern and western cities.

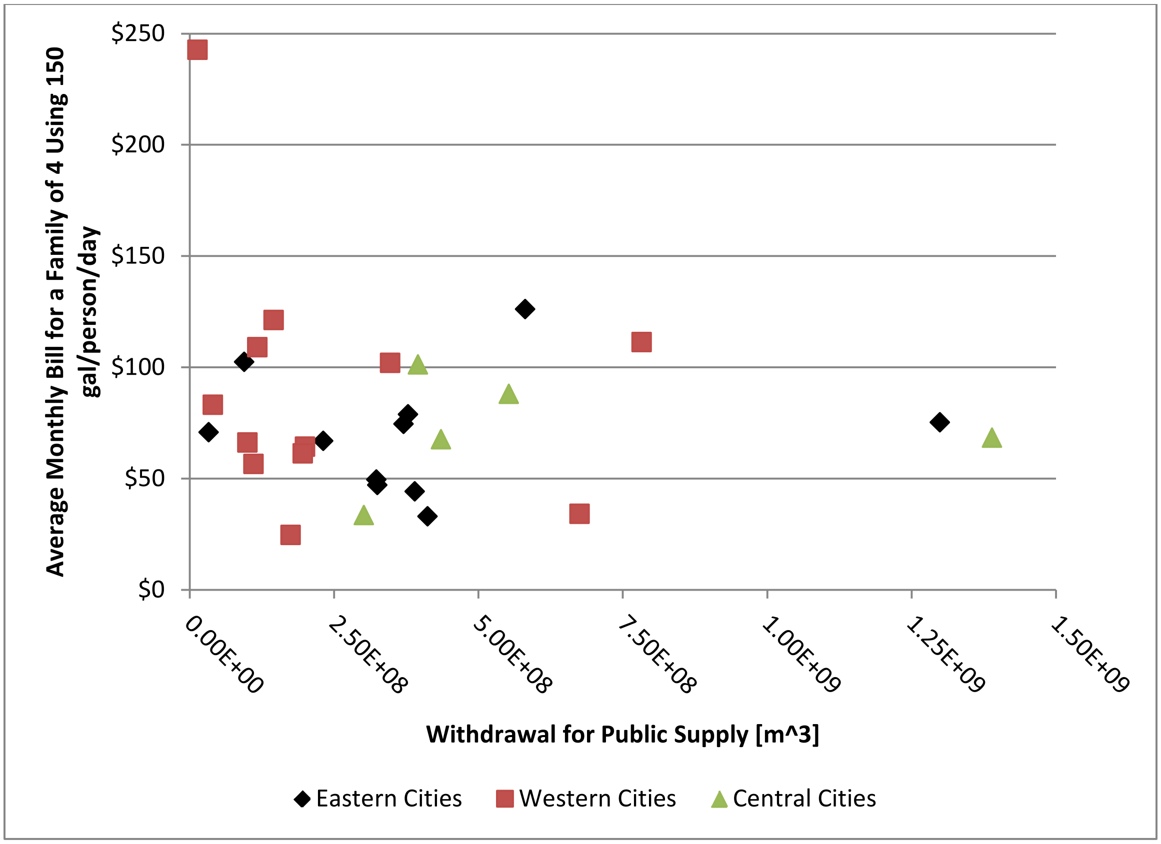

Figure 5-7 Plot of annual total withdrawal for public supply vs the average monthly bill for a family of 4 using 150 gal/person/day

Looking at total WSI versus water prices, shown in Figure 5-8, there is also no clear change in price as a response to WSI, especially in the West. In the Eastern and Central cities, there is perhaps a weak inverse relationship where total WSI is higher in cities with lower average water rates. However, isolating the fraction of WSI due to public supply versus prices, shown in Figure 5-9, it can be seen that there is a weak positive correlation between increasing price and increasing fractional WSI. This suggests that price may be increasing as a policy measure when a greater proportion of local water stress is due to public sector users.

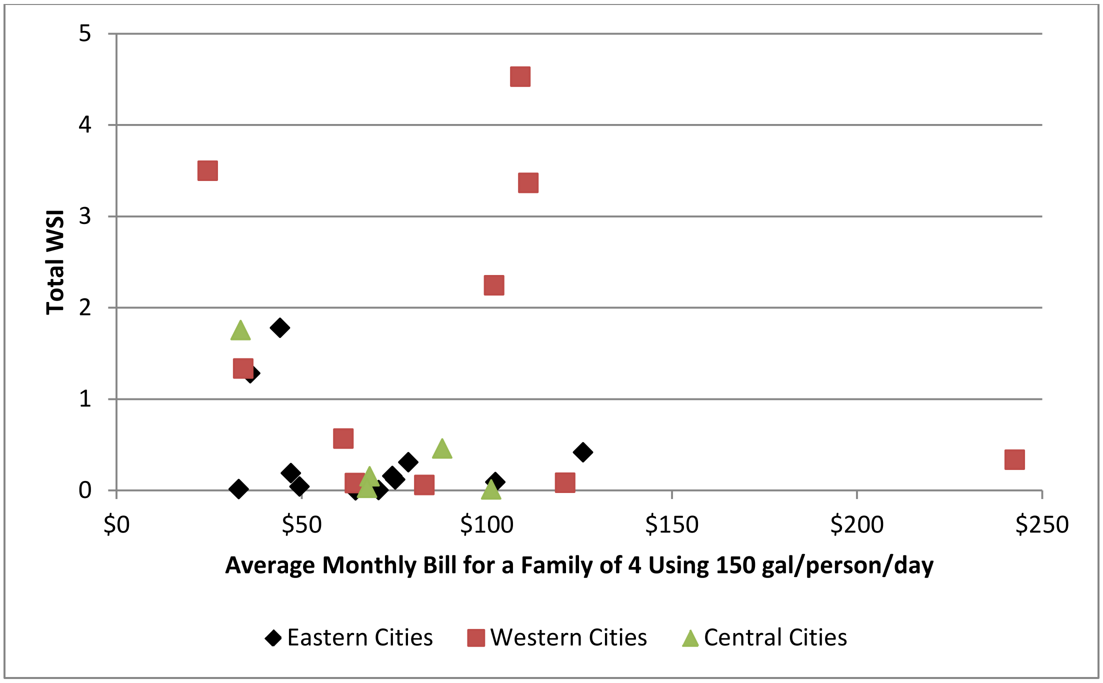

Figure 5-8 Plot of the average monthly bill for a family of 4 using 150 gal/person/day vs total WSI

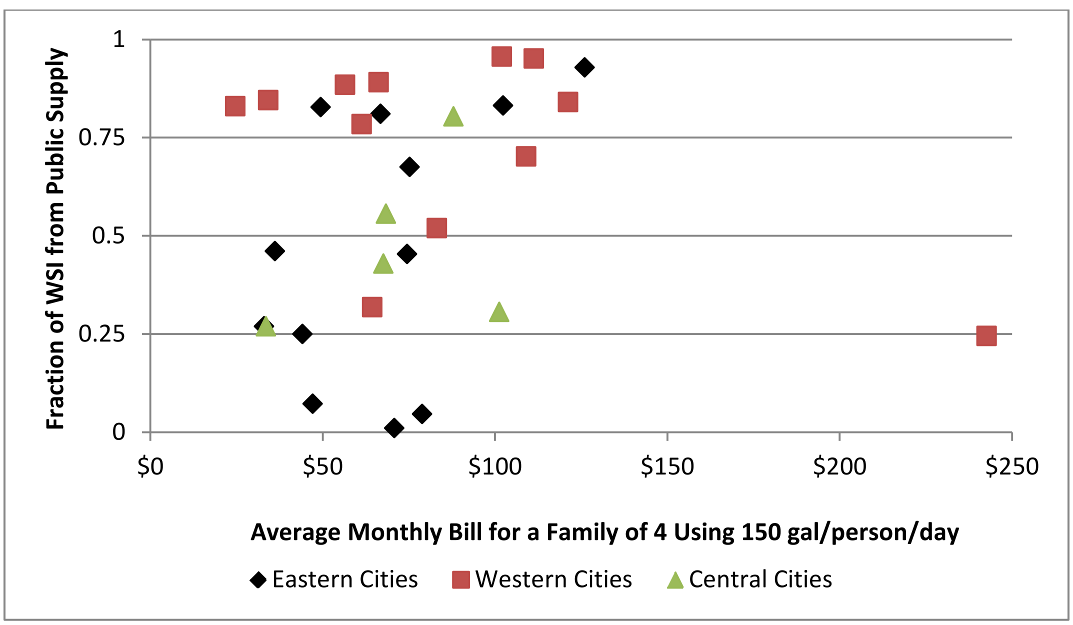

Figure 5-9 Plot of the average monthly bill for a family of 4 using 150 gal/person/day vs fraction of WSI from public supply

One would expect that public water use withdrawals will coincide with population centers and therefore, the fraction of overall water stress tied to public supply will as well. Water withdrawals do not necessarily take place in the same small watershed as the population, however, resulting in a spatial offset in the location of water stress relative to population. This offset was addressed to some extent by aggregating to the 8-digit HUC level, by averaging the total WSI of all 10-digit HUC watersheds within the 8-digit HUC boundaries. Figure 5-10 and 5-11 show the relationship between average 8-digit HUC population and average 8-digit HUC WSI for the East and the West, respectively.

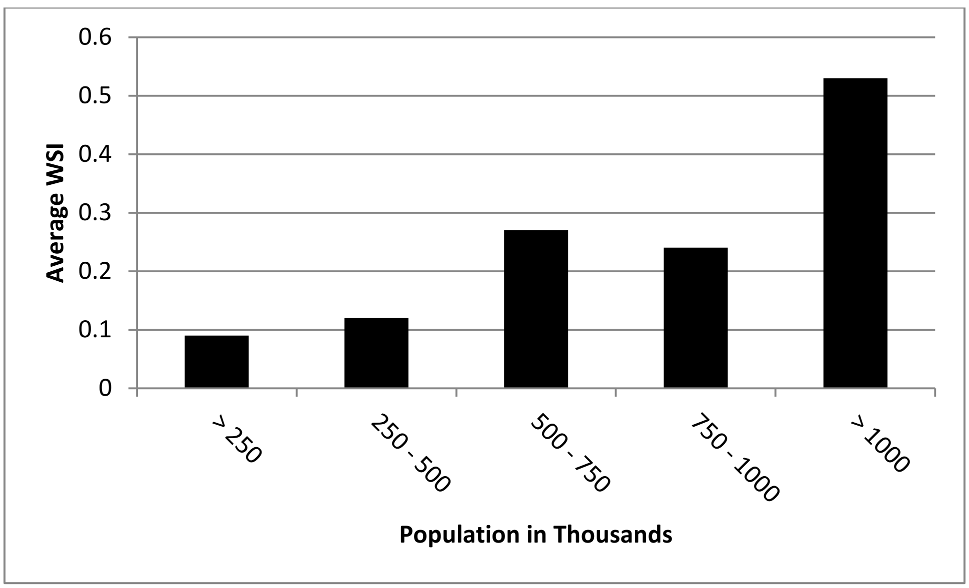

Figure 5-10 Average WSI for all HUC8 watersheds within population ranges for the South Atlantic Gulf

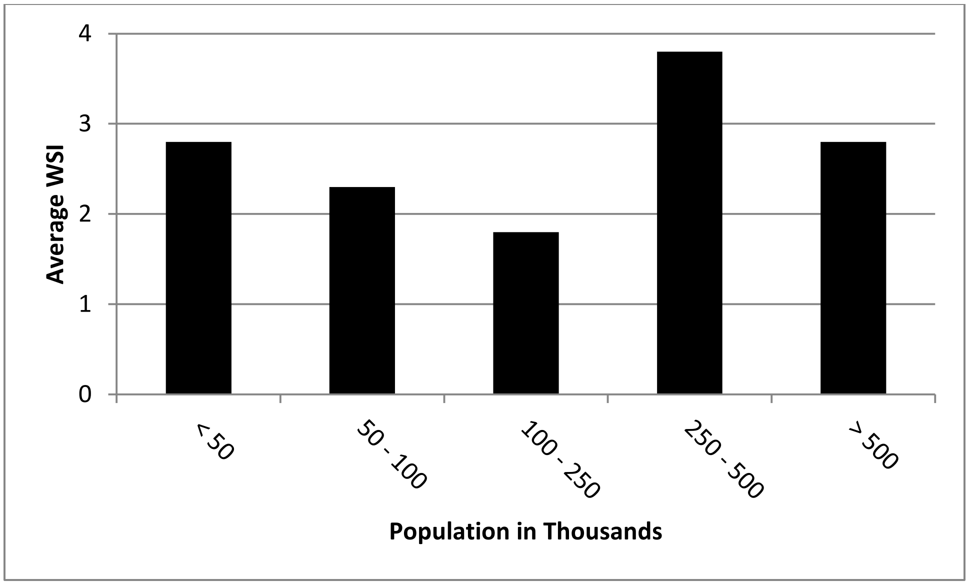

Figure 5-11 Average WSI for all HUC8 watersheds within population ranges for the Colorado River Basin

Figure 5-10 shows a strong connection between larger population values and high water stress in the East. The same is not true for the West, which has high WSI values independent of population (Figure 5-11).

5.3 Irrigation and Supply

Irrigated acres, as well as the fraction of irrigated farmland, are being used as indicators of limited supply in the next part of the analysis. To test the hypotheses that water stress is influenced primarily by limited supply in the West, the number of irrigated acres of farmland in each state was compared to supply and the fraction of WSI from irrigation. First, the fraction of WSI from irrigation values was averaged over the entire state because the Agricultural Census only provided information by state. The scaling processes used earlier in the analysis to determine withdrawals by 10-digit HUC were originally reported by county. Trying the same method from a state scale would degrade the information for the purpose of this analysis.

As shown in Figure 5-12, the fraction of WSI from irrigation for all but one of the Colorado River Basin states is greater than 75%, while it is less than 50% for the South Atlantic Gulf states.

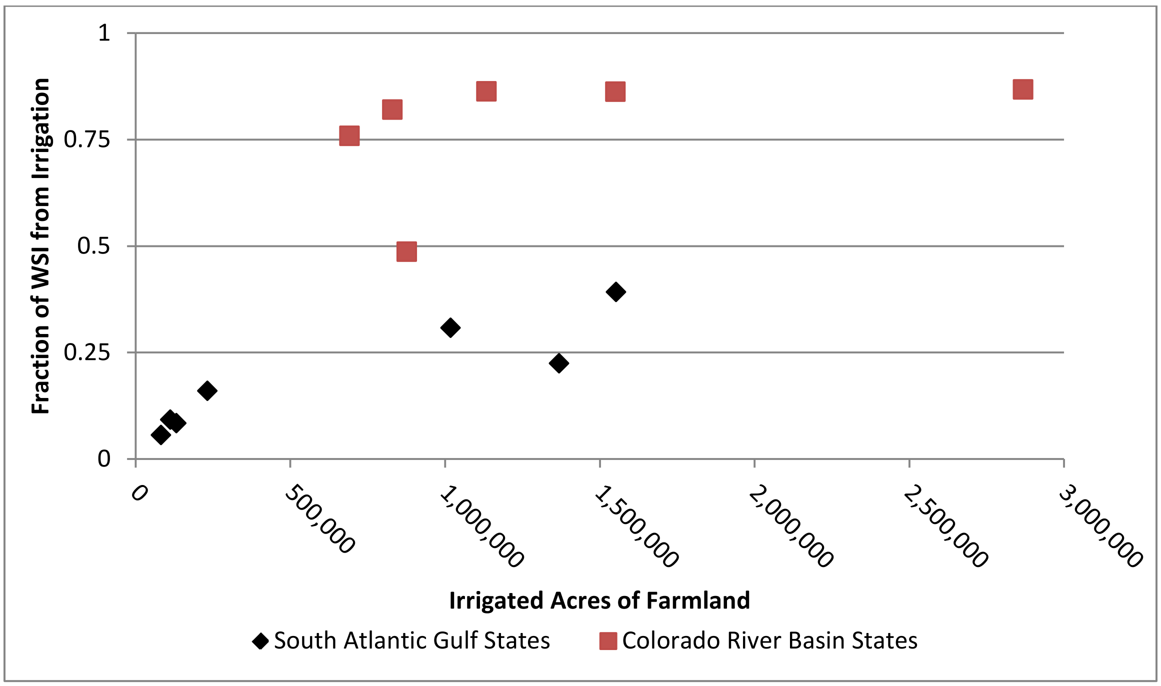

Figure 5-12 Plot of irrigated acres of farmland vs average fraction of WSI from irrigation by state

However, if locally generated supply normalized by total area is compared to the fraction of farmland which is irrigated, the fraction of irrigated farmland is somewhat independent of the supply depth in both regions, as shown in Figure 5-13. It is important to note that Colorado has the highest amount of supply, the largest total irrigated area and the largest fraction of irrigated area; additionally, Colorado includes the headwaters for the other states in the basin, except Wyoming which has the second highest volume of water.

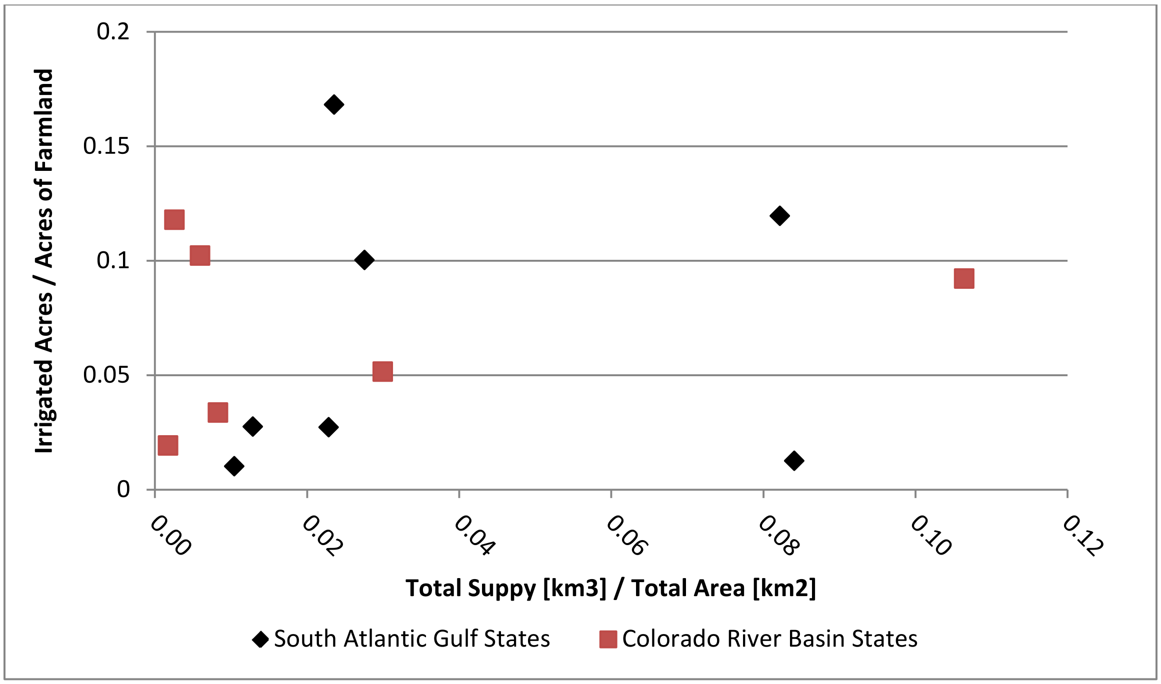

Figure 5-13 Plot of normalized water supply vs fraction of total farmland that is irrigated

5.4 Comparison between Southeastern and Southwestern United States Water Stress

In the different regions in the United States, different boundaries are more appropriate when investigating water stress. Interactions between ecological and geopolitical boundaries influence water stress and create variability when analyzing at different scales.

The size of the dominant spatial control, or most important underlying variability, is crucial when reporting an accurate representation of water stress across the United States. If country withdrawals are the dominant control on water stress index, then the HUC boundary that best matches the county boundary should be used. However, if dense population centers are dominant, then a resolution which shows this connection should be used.

Even the language between eastern water disputes and western water disputes suggests a different foundation for water related issues. The Eastern disputes tend to argue over which water user has a greater need; in other words, they are demand oriented. For example, Atlanta's expanding population generates increased demand, conflicting with aquaculture demand downstream (Couch et al., 1996). Conversely, the Western disputes require engineers to analyze the hydrologic system in order to determine available water supply and depletion due to water projects; the focus is quantity of water rather than type of use (Meyers, 1966). Limited supply is the primary concern when negotiating water allocations among the southwestern states.

The WSI maps shown in Figures 5-1 and 5-4 illustrate pervasive differences in the spatial structure of water stress between the South Atlantic Gulf Region and the Colorado River Basin. Water stress is mostly high and more uniform when isolating the Colorado Basin, while it is mostly low, with some high spots in the South Atlantic Region. Although watersheds are bigger in the West with only one major river system, both regions have strong sub-regional controls on ground water and surface water use, with surface water use in the headwaters and groundwater use in the lower basins. Looking at the effects of use sectors, once again both basins have strong regional controls on public supply versus irrigation, where public supply dominates in the Piedmont in the East and Northern Arizona in the West. Irrigation dominates in the Coastal Plains in the East and throughout the West. Due to the differences in population location there is a fundamental difference in that irrigation comes from surface water in the west, but from groundwater in the east.

There is no clear relationship between water price and overall demand or WSI in major urban centers, but there is an increasing price when a greater proportion of local water stress is due to public sector users. Population density was the best indicator showing total WSI increases with population in the East, but is universally high in the West. Fraction of WSI from irrigation is uniformly higher in the west, as is the number of irrigated acres. Population centers have controlling factor on water stress in the East as shown in the population density versus average WSI comparison. However, water stress generated by supply limits in the West could not be shown through regional studies, but rather the national scale maps comparing runoff and stress.

CHAPTER 6. CONCLUSIONS

6.1 Summary

Water stress is used to express the inability to meet human demand given available supply; however, the complexity of temporal and spatial variability of available fresh water complicates the analysis of water stress (Oki et. al., 2001; Sabo et al., 2010). By evaluating the appropriateness of previous WSI results relative to spatial scale, policy makers will have more pertinent information to base their decisions. In this study, national scale datasets on water withdrawals, along with simulated water supply were used to perform a GIS-based analysis on the regional controls of water stress in the United States. Additionally, a regional case study was used to investigate the claims that stress is supply limited in the West and demand driven in the East.

6.2 Science Questions

The overall goal of this project was to investigate the spatial controls on water stress across the United States. Chapter 4 explored how the water stress index varies nationally as a function of spatial scale, supply, and demand. When calculating WSI at low resolutions, WSI hot spots corresponding to population centers in the East are smoothed. Additionally public supply withdrawals cause at least 50% of the water stress in these hot spots, supporting the hypothesis that water stress variability is driven by population centers in the eastern United States. Conversely, in the West widespread irrigation withdrawals correspond to areas of limited supply resulting in large areas of high water stress unaffected by spatial scale.

Chapter 5 addressed the science question of how the water stress index varies in relation to ecoregion, political accounting units, population, price, and irrigation needs by comparing two hydrological regions in the United States: the South Atlantic Gulf and the Colorado River Basin. For the South Atlantic Gulf, patterns of water use correspond to ecological settings. Surface water withdrawals dominate the Appalachian foothills where high precipitation generates excessive runoff, while ground water withdrawals are high along the coastal plains where soil conditions allow rapidly recharging, high water tables. However, most notable it is the pattern of high WSI matching high population density that best supports the claim that averaging over large areas masks stress in and around large cities.

Investigating potential controlling forces of water stress in the East versus the West, price, population density, and irrigated farmland were compared to the WSI values. Price was not a good indicator for demand driven water stress. As stress or demand increased, there was no relationship to increasing price rates. Additionally irrigated farmland was not an applicable indicator for supply limited water stress, as no clear relationship between the two was seen. Population density did demonstrate a strong relationship to WSI in the East but not the West. In the East, WSI increases with increasing population density, where high average WSI values are not affected by population totals in the West (Figure 4-13 and 4-14).

The final science question addressed the dominant control on the spatial variability of water stress index in the eastern versus the western United States. As a metric for indicating unsustainable water usage, WSI is only useful when the values reflect accurate trade-offs between supply and demand. Due to spatial variability, calculations should be performed at the highest practical resolution to preserve the effects of the dominant control on spatial variability. From the results, there is some support for the claim that competition in the East between types of water users leads to high WSI values around population centers, driven by the demand part of the ratio. Therefore, in order to take appropriate actions to reduce water stress, calculations need to be at smaller local watershed levels rather than at large regions. In contrast, no contradicting evidence was generated to suggest water stress in the West is not driven by the supply portion of the ratio nor dependent on spatial scale. However, due to the water withdrawal data being reported at large county scales, the WSI values did not aggregate down to 10 digit HUCs well. It is recommended that given the two WSI maps generated by Sabo et al (2010) and this project, WSI values for the western United States be at the 4 digit HUC and WSI values for the eastern United States be at the 10 digit HUC.

6.3 Directions for Future Work

Only one indicator, population density in the East, showed a relationship with high WSI values. Overlapping many possible boundaries, both geological and ecological, to determine the best possible scale for each region in the United States could provide an interesting perspective on the spatial variability of water stress. Future studies could incorporate social constraints on water stress within the various boundaries as a way to understand human impacts beyond physical withdrawals and infrastructure.

REFERENCES

REFERENCES

"2010 United States Census Gazetteer for Places: January 1, 2010" (text). *2010 United States Census*. United States Census Bureau. April 2010. Retrieved August 1, 2012.

Alcamo, J. et al. (2003): Global estimates of water withdrawals and availability under current and future “business-as-usual” conditions, Hydrological Sciences Journal, 48:3, 339-348

Apple, D.D. 2001. Evolution of U.S. Water Policy: Emphasis on the West

Cherkauer, K.A., Variable Infiltration Capacity (VIC) Cold Land Process Model Updates, *Global and Planetary Change*, 38(1-2), 151-159, 2002.

Couch et al., 1996 “Influences of Environmental Settings on Aquatic Ecosystems in the Apalachicola-Chattahoochee-Flint River Basin” US Geological Survey Report 95-4278

Falkenmark, M. “Society’s Interaction with the Water Cycle: A Conceptual Framework for a More Holistic Approach,” *Hydrological Sciences* 42, no. 4 (1997): 451–66.

Kenny et al., 2009. “Estimated use of water in the United States in 2005,” *US Department of the Interior, US Geological Survey,* cir1344

Liang X et al., (1996) One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model. J Geophys Res 101(D16):21403–21422.

Liang, X. et al., A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs, *J. Geophys. Res.*, 99(D7), 14,415-14,428, 1994.

McNab, W.H. et al., 2007. “Description of ecological subregions: sections of the conterminous United States [CD-ROM]”. Gen. Tech. Report WO-76B. Washington, DC: U.S. Department of Agriculture, Forest Service. 80 p.

Meyers, C.J. “The Colorado River,” *Stanford Law Review* 19 (1966)

Oki, T.Y et al., 2001. Global assessment of current water resources using total runoff integrating pathways, Hydrol. Sci. J., 46, 983–995

Oki, T.Y., Kanae A.S.. Global Hydrological Cycles and World Water Resources Science 25 August 2006: 313 (5790), 1068-1072. [DOI:10.1126/science.1128845]

Sabo, J.S.**,** (2010) Reclaiming freshwater sustainability in the Cadillac Desert. *Proceedings of the National Academy of Sciences* (USA) **107** (50) 21256-21262.

Seaber, P.R., et al. (1987) *Hydrologic Unit Maps: U.S. Geological Survey Water-Supply Paper 2294* (USGS, Reston, VA)

Sherk, G.W. “Resolving interstate water conflicts in the eastern United States: The re-emergence of the federal-interstate compact” *Water Resources Bulletin* 30, no. 3 (1994) 397:408.

Shiklomanov, I.A. “Appraisal and Assessment of World Water Resources,” *Water International* 31, no. 1 (2000): 11-32.

Seyfried, M.S. and Wilcox, B.P. (1995). Scale and the nature of spatial variability: Field examples having implications for hydrologic modeling. *Water Resources Research 31(1): doi: 10.1029/94WR02025. issn: 0043-1397.*

U.S. Geological Survey (2010) Estimated use of water in the United States county-level data for 2005. Available at http://water.usgs.gov/watuse/data/2005/.

United States National Atlas (2010) Streams and waterbodies of the United States. Available at http://nationalatlas.gov/mld/hydrogm.html.

Vorosmarty et al. (2010). Global threats to human water security and river biodiversity. *Nature 467: doi:10.1038/nature09440.*

Water Policy Institute, (2009) Water Wars: Conflicts over Shared Waters. *A Case Study of the Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa River Basins.*http://www.huntonfiles.com/files/webupload/WPI_Water_Wars_White_Paper.pdf

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